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WADC TECHNICAL REPORT 55-383

PART I

FC

**REDUCTION OF TURBINE ENGINES
NOISE LEVELS AT THE SOURCE**

Part I. Survey of Theoretical and Experimental Data

MICHAEL D'INNOCENZIO

CURTISS-WRIGHT CORPORATION

SEPTEMBER 1955

WRIGHT AIR DEVELOPMENT CENTER

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SEPTEMBER 1955

POWER PLANT LABORATORY
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**WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This report was prepared by Michael D'Innocenzio of the Research Division, Curtiss-Wright Corporation, in partial fulfillment of Contract No. AF33(616)-3140, under WADC Project No. 7211, "Acoustic Energy Sources," Task No. 30212, "Reduction of Turbine Engine Noise Levels at the Source." This work was administered under the direction of the Powerplant Laboratory, WCLPR, Wright Air Development Center, with Mr. G. E. Terpenny acting as project engineer.

This document is the first prepared under Contract No. AF33(616)-3140. Further research is being conducted on "Reduction of Turbine Engine Noise Levels at the Source" and will be published in future parts of this report.

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ABSTRACT

Aerodynamic noise generation has been the subject of extensive investigations both in this country and abroad. A survey of this available theoretical and experimental data on aerodynamic noise generation has been made to aid in establishing the present "state of the art" in the field of turbojet engine noise generation and control.

Methods of analyzing and predicting noise levels are presented and evaluated. The efforts of several investigators in the development of jet noise suppression devices are reviewed.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

for *E. C. Phillips*
NORMAN C. APPOLD
Colonel, USAF
Chief, Power Plant Laboratory
Directorate of Development

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I. INTRODUCTION

A great deal of effort has been expended in attempts to control the noise generated by jet-powered aircraft to protect aircraft maintenance crews and nearby inhabitants from hearing damage and annoyance. In addition to personnel hazard and neighborhood complaints, there are records of structural failure of aircraft components due to the energies and frequencies propagated by jet noise. Unfortunately, the existing problem will be further aggravated by current and proposed supersonic aircraft requiring increased mass flow and higher thrust propulsion systems. This demand for higher design speeds and thrusts may possibly double present sound levels, thereby adding considerably to the problem of noise abatement.

Contractors involved in the development of high performance jet aircraft should possess an adequate understanding of the mechanisms by which aerodynamic noise is generated and propagated. With this insight, it might be possible for the designer to predict the noise levels of proposed powerplants during the initial stages of design and, if necessary, to take appropriate steps to reduce the noises generated to a tolerable value.

The basic theory of the origin, propagation, and reception of sound was proposed initially by the ancient Greeks, but the efforts of eminent investigators such as Rayleigh, Helmholtz, Toepler, Mach and Sabine raised the initial hypotheses to the level of a science by rigorous correlation of theories and experimental data. However, in the development of the science of acoustics, a small phase, aerodynamic jet noise generation received little or no attention by these investigators. Not until recent years, through the work of Lighthill in England (1*), were some concepts by which jet noise is generated actually developed. Previous to this time, the mechanisms involved in the generation of noise from jet streams were not known; as a result, investigators lacked the tools to predict the intensity of the jet noise from the available fluid flow parameters.

In Great Britain and the United States, experimental programs have been or are being conducted at leading universities and government facilities to study the problems of jet noise. Considerable progress has been made. In fact, it may be said at this time that the basic phenomena of aerodynamic jet noise are now understood. A theory and a method have been developed which permits the prediction of jet noise levels and personnel reaction to predetermined noise levels.

The following paper is a review and evaluation of technical efforts to date in the field of aerodynamic noise generation and control. An attempt is made to understand the problem of aerodynamic noise in terms of the physiological and psychological effects on the human being since at the moment, the basic problem stems from the necessity of protecting the human being from the enormous acoustical energies radiated by jet-powered aircraft.

*Refer to Bibliography

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II. CHARACTERISTICS AND EFFECTS OF NOISE

The ear has the inherent ability to resolve the phenomenon of sound (see Appendix A) into its various frequency components and to judge its loudness and pitch. The reception of sound by the ear can be expressed in terms of certain physical properties, one of these being the pressure of the transmitting medium. Pressure variations in the medium from an initial or equilibrium value which arise as a result of sound propagation are usually referred to as sound pressure or "excess" pressure. Since the range of sound pressures audible to the human ear can cover a wide range, it has become common practice to express sound pressure (as well as other acoustical properties) as a logarithmic relation for the sake of convenience. Thus the SOUND PRESSURE LEVEL is defined as:

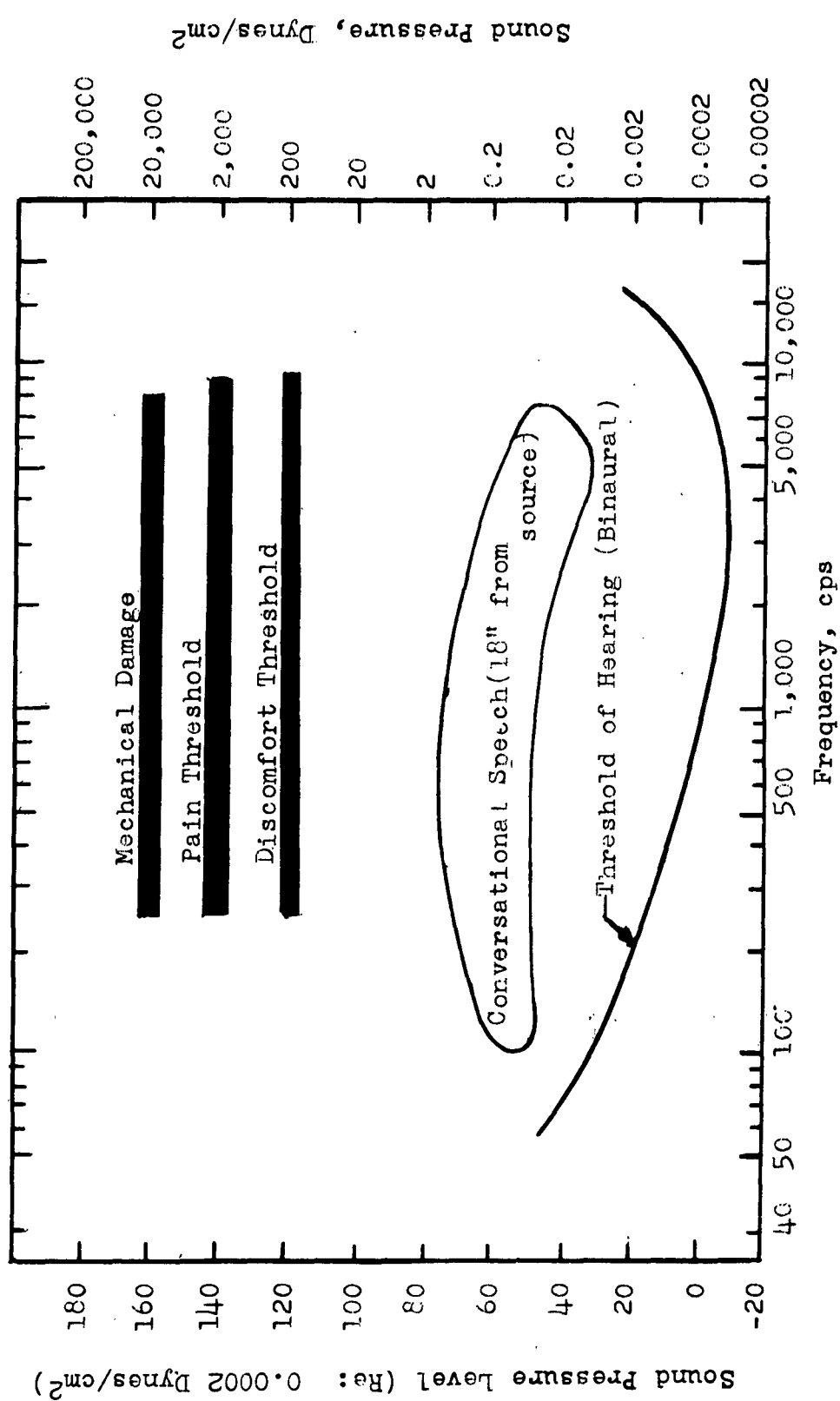
$$SPL = 20 \log_{10} \frac{(\text{RMS value of sound pressure})}{(\text{Reference sound pressure})} \quad (I)$$

The units of SPL are decibels, (db). Several reference pressures have been used by workers in the field; however, the most common value, which has been arbitrarily selected, is 0.0002 dynes/cm². This value corresponds to a sound intensity of 10⁻¹⁶ watts/cm², for standard air, which is the minimum audible intensity of a 1000 cycles per second, (cps), tone for the average ear. SOUND INTENSITY can be considered as the time rate of transfer of the generated sound energy per unit area perpendicular to a specified direction. It has the units of watts/cm². Expressed in logarithmic form it is known as INTENSITY LEVEL:

$$IL = 10 \log_{10} \frac{(\text{intensity of sound})}{(\text{reference intensity})} \quad (II)$$

The reference intensity is usually taken to be 10⁻¹⁶ watts/cm² since it corresponds to a plane or spherical sound wave having a sound pressure of 0.0002 dynes/cm². The unit of intensity level is the decibel, (db).

The range of audibility of the ear is shown by Figure 1. The pressure variation required at each frequency to just arouse a sensation of hearing is indicated by the curve labeled "threshold of hearing." While the normal range of hearing, i.e., the audible range, extends from about 20 cps to 20,000 cps, the sound pressure required to arouse a sensation of sound is not the same at all frequencies. Data from numerous subjective tests show that sounds having pressure levels of 120 db and 140 db produce a feeling of discomfort and pain, respectively. If the sound pressure level is greater than 160 db, permanent damage can occur to the mechanism of the middle ear. Exposure to an intense noise for a short period of time raises our threshold of hearing which means that for a given tone to be audible, its intensity must be increased. In such situations, traumatic deafness (temporary deafness) can occur. Figure 2 illustrates

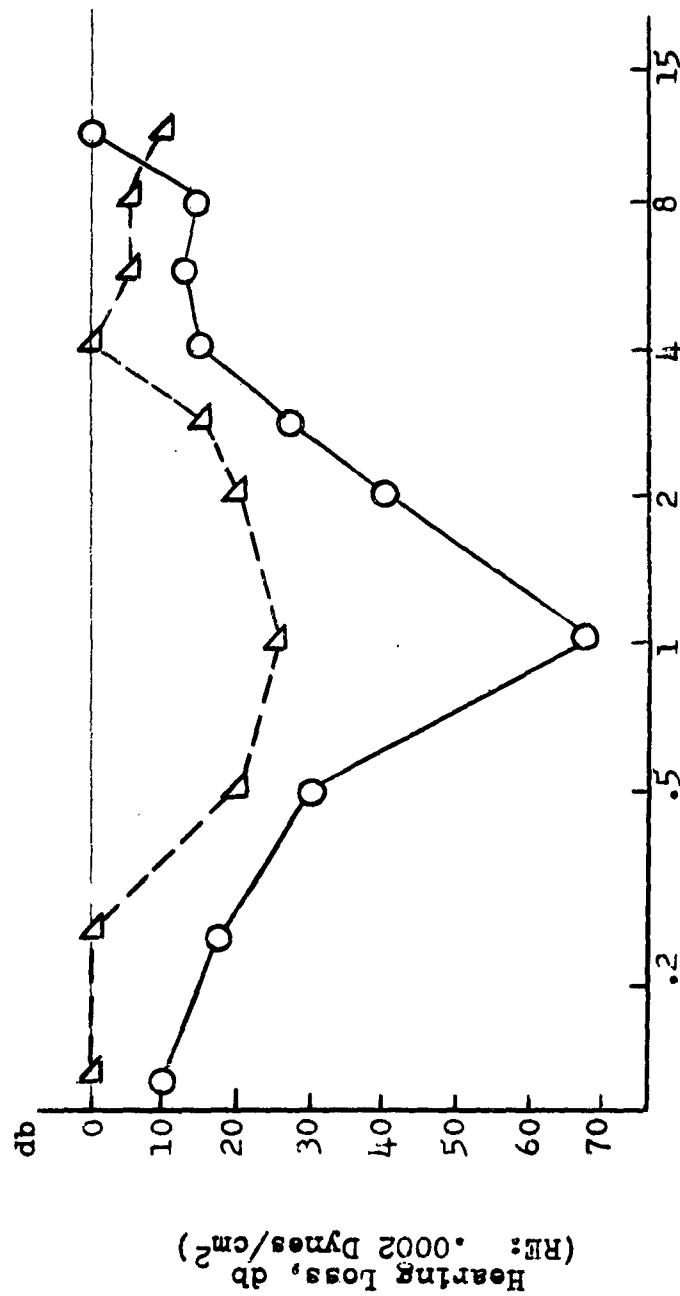


Thresholds of Sound

Figure 1

Distance: 6 Ft. Aft of J-33 Engine Tailpipe
Data Taken 12 Minutes Later

△ 3 1/4 Min. Exposure, SPL = 142 db
○ 10 Min. Exposure, SPL = 146 db



Frequency, Kilocycles/Second

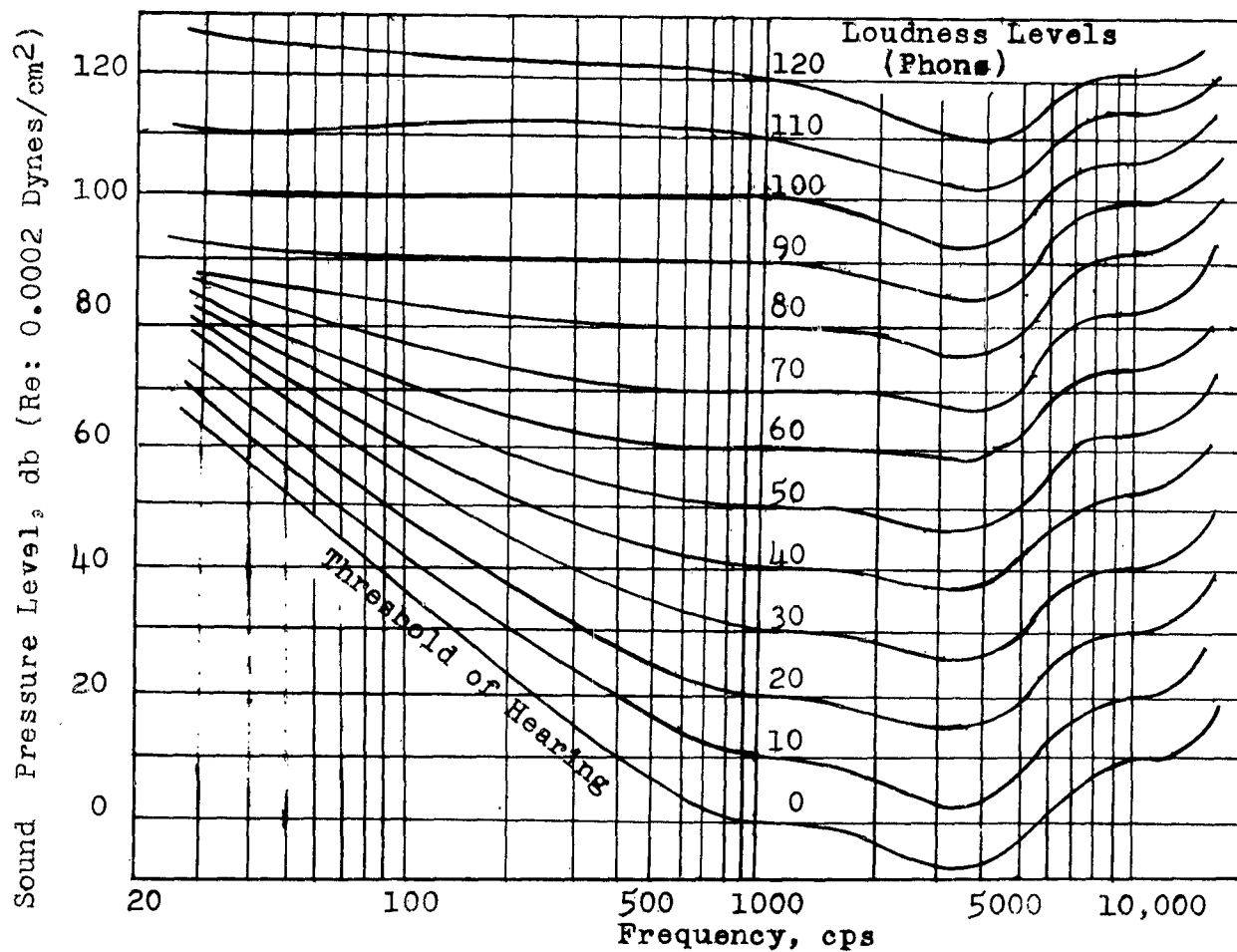
Traumatic Deafness Caused by Exposure to Jet Engine Noise

Figure 2

the loss in hearing which resulted from the exposure to a jet engine noise field. Repeated exposure to noise levels which cause traumatic deafness have resulted in cases of permanent deafness (2, 3, 4). Personnel should not be exposed to intense sound levels of 140 db or greater unless protective gear is worn in addition to the standard ear plugs.

Data has been obtained which indicates other deleterious effects of sound. At SPL of 140 db and greater, within the frequency range of 700 to 2,000 cps, the head perceives a strong sensation of skull vibration while the chest wall, abdominal wall, arm and leg muscles are also set in vibration at these conditions. It has also been found that at these high pressure levels, there is a mild heating of exposed body surfaces for frequencies between 3,000 and 25,000 cps. Strong sound field exposure can sometimes cause conditions such as vomiting, nausea, headaches, and hyper-irritability. Airborne ultrasonic waves, it appears, do not damage the central nervous system and sense organs unless the head structure is placed in physical contact with the generating sound source (5). Since jet engine noise is predominantly audible sound, the ultrasonic portion of the sound spectrum does not enter into the problem of jet engine noise at this time.

The ear, though quite sensitive to pressure, has limited frequency response - responding to some frequencies better than others. Thus, two sounds of equal intensities but at different frequencies may sound of different loudness. The Fletcher-Munson curve of Figure 3 indicates the levels of tones which sound equally loud, i.e., those tones which have the same loudness level. LOUDNESS LEVEL is defined as the sound pressure of a 1,000 cps tone which sounds, to the human ear, as loud as the sound in question. It has the unit of phons. However, the loudness level concept does not indicate how much louder one sound is than another. In order to indicate this, we resort to the concept of loudness. LOUDNESS is defined as the relative positioning of a sound on a scale in the order of "soft" to "loud" as determined by the ear. The scale is set up so that sounds are compared in loudness to a sound having a frequency of 1,000 cps at a sound pressure level of 40 db. The units of loudness are called sones. The transfer function curve, Figure 4, is used for determining the relative loudness of sounds. As an example of the use of these curves, suppose that a source emits a 500 cps sound having a SPL = 100 db at a given position in the sound field (note that for SPL > 90 db and frequencies < 1500 cps, the loudness level curves are almost independent of frequency). Suppose now that the intensity of this sound is reduced so that the SPL = 91 db. Figure 3 indicates that for the sound having a SPL = 100 db, the loudness level = 100 phons, while for a SPL = 91 db, the loudness level = 91 phons. Using the transfer function, these correspond to loudness units of 100 sones and 50 sones, respectively. Thus, it is noted that the loudness has been reduced by fifty percent for a nine percent reduction in db.



Fletcher-Munson Equal Loudness Contours

Figure 3

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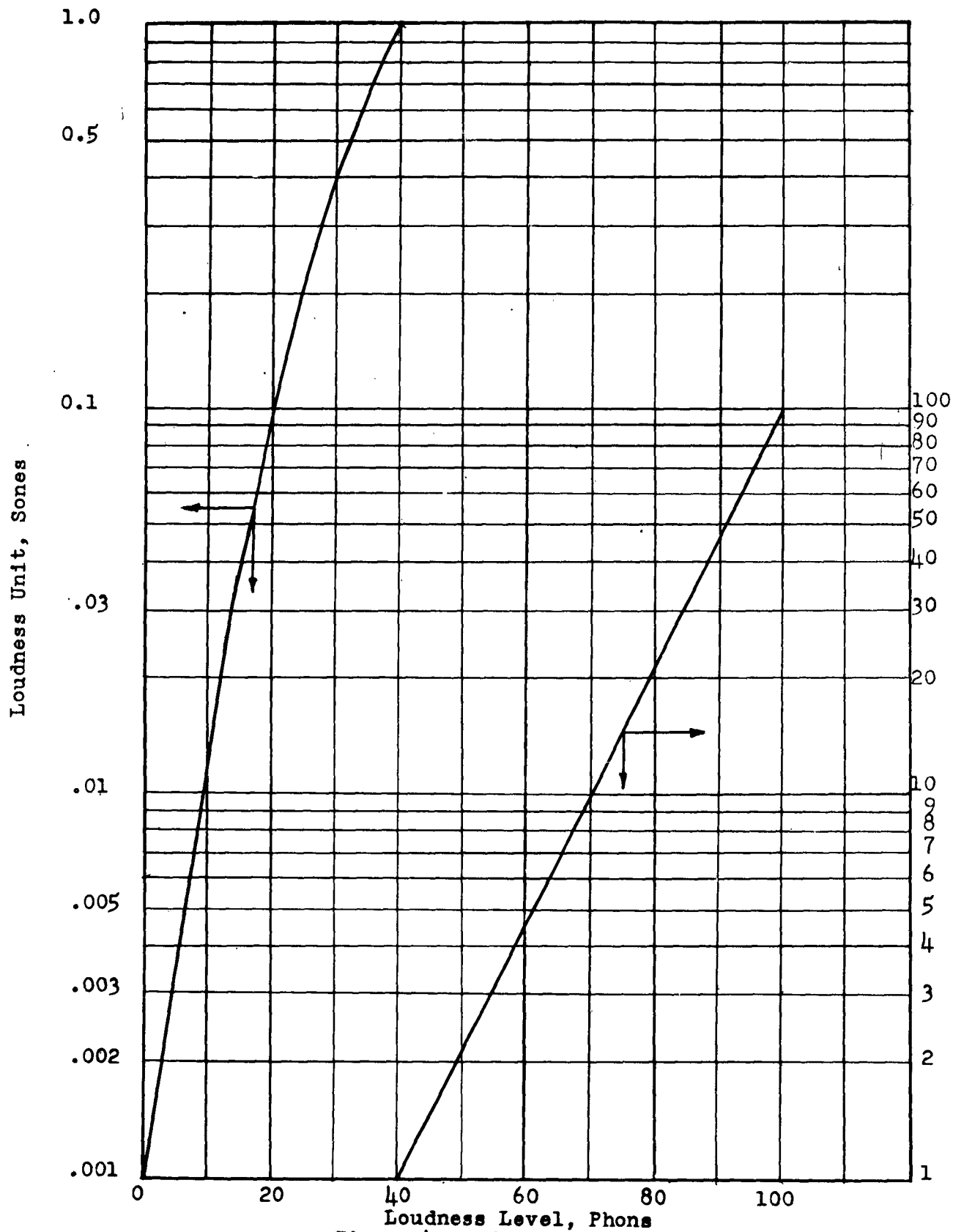


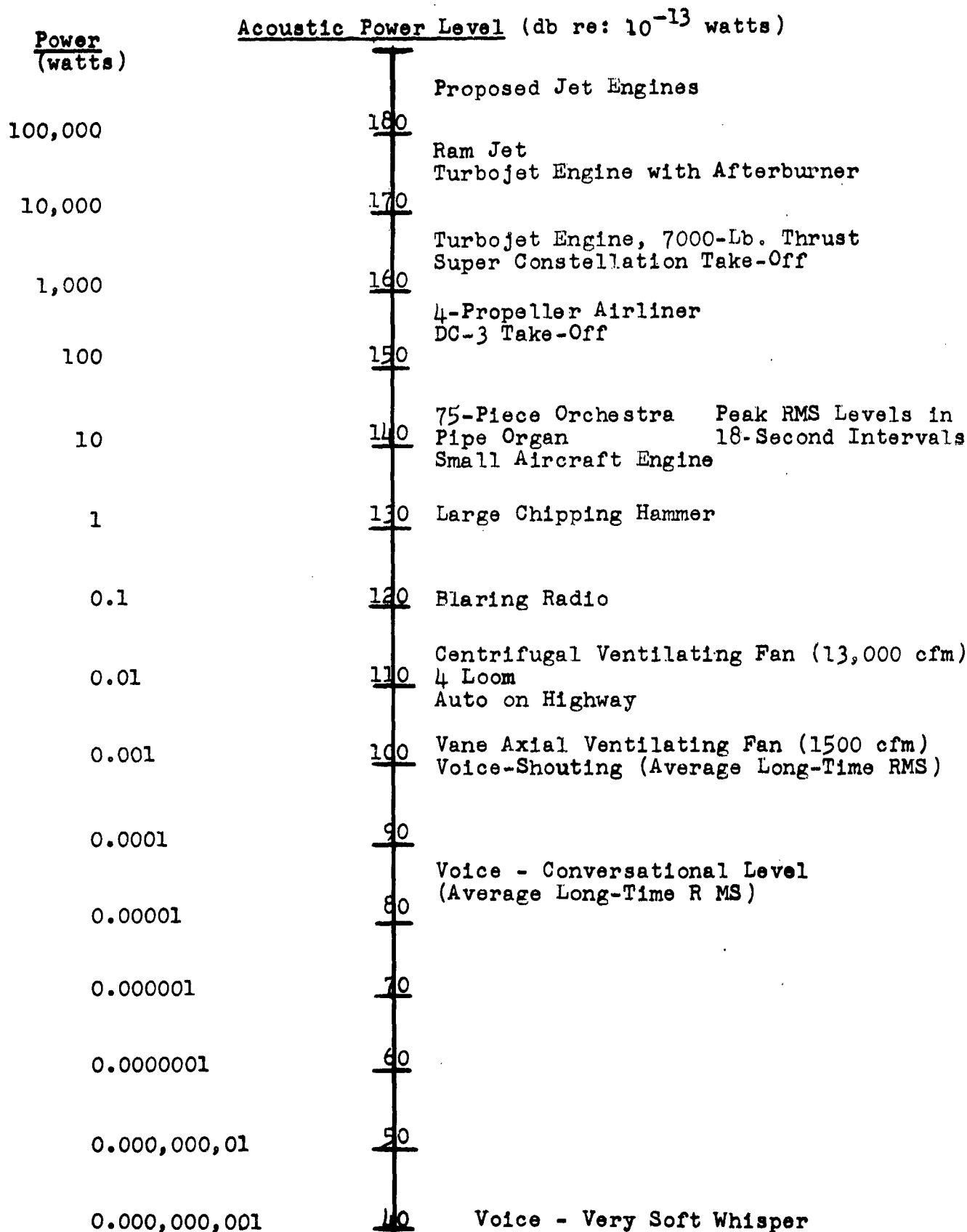
Figure 4. - Transfer Function

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Sound, like other wave phenomena, is primarily a transfer of energy. The power of a source can be expressed in a logarithmic manner; therefore, the SOUND POWER LEVEL is defined as:

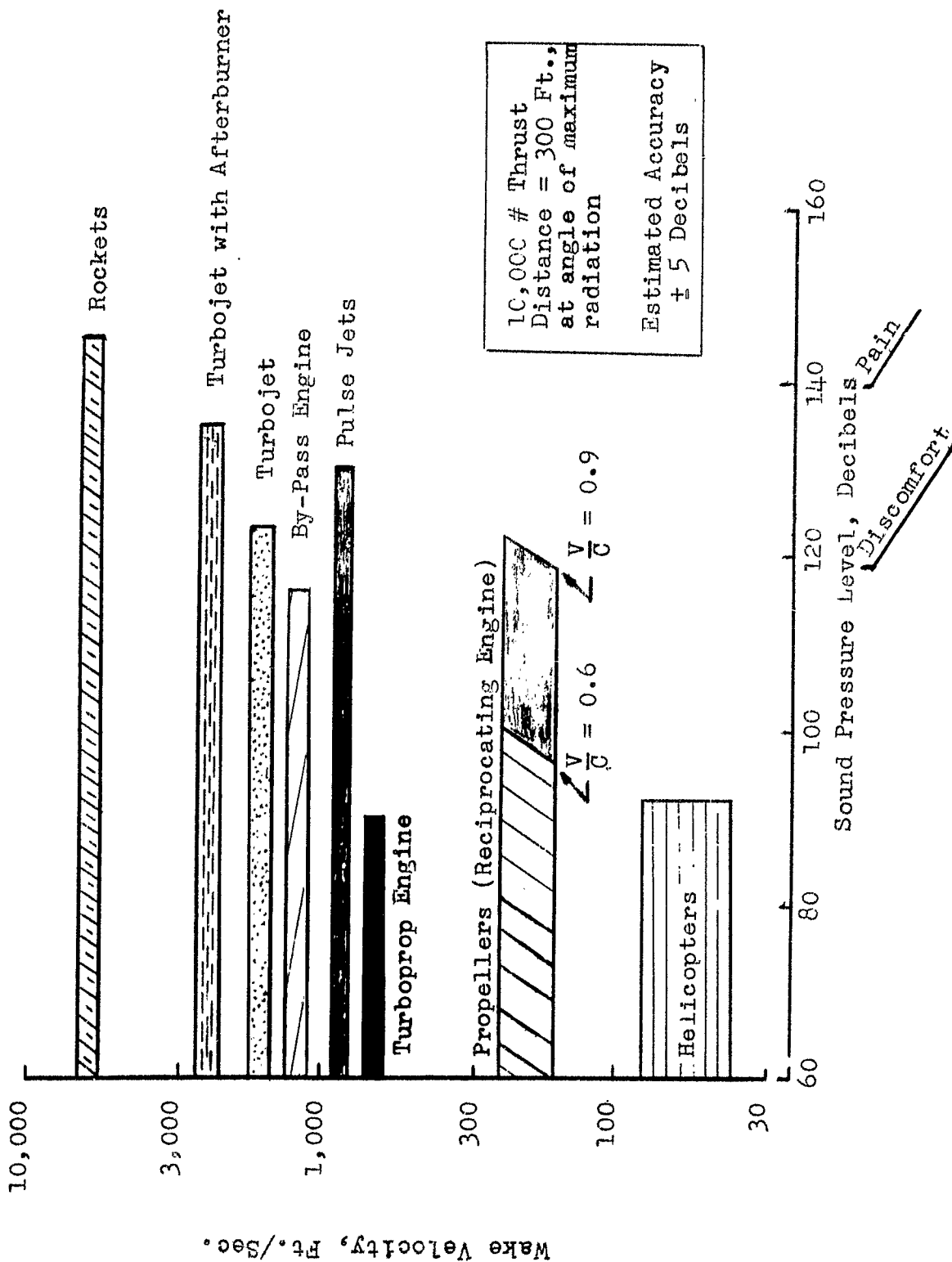
$$PWL = 10 \log_{10} \left(\frac{\text{acoustic power}}{\text{reference acoustic power}} \right) \quad (III)$$

The reference acoustic power is usually taken as 10^{-13} watts; the unit of sound power level is the decibel. In Appendix B, a method is presented whereby sound power level can be determined for a noise source. Typical values of acoustic power generated by several familiar noise sources are shown by Figure 5, while the noise levels of various aircraft propulsive systems are indicated by Figure 6. The acoustic pressures associated with aircraft propulsion systems lie in the decibel range where pain or damage to the ear can occur. For the same thrust, the turbojet engine and the rocket generate the greatest amount of noise compared to other types of powerplants. This is due mainly to the jet nozzle - a tremendous noise generator which these systems employ. The data of Figure 7 indicate jet-powered aircraft produce louder noises than other type aircraft during take-off operation, whereas during the landing approach, jet aircraft noise is somewhat less than other aircraft for the same time interval (6). Comparison of these data on the basis of equal aircraft weight (since engine noise and power can be said to be proportional to aircraft gross weight) shows that jet-powered aircraft produce approximately 9 db more noise during take-off than aircraft propelled by reciprocating engines.



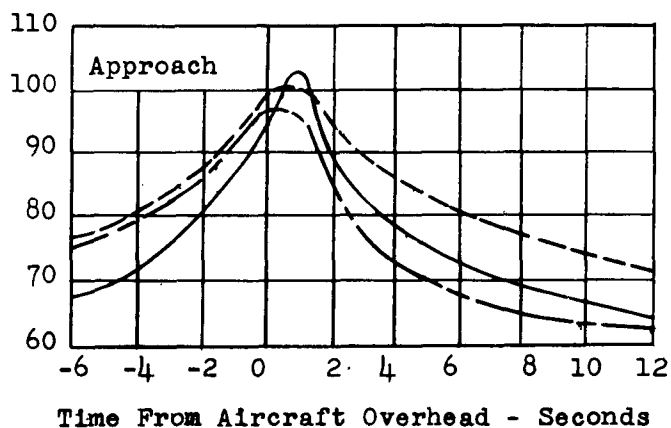
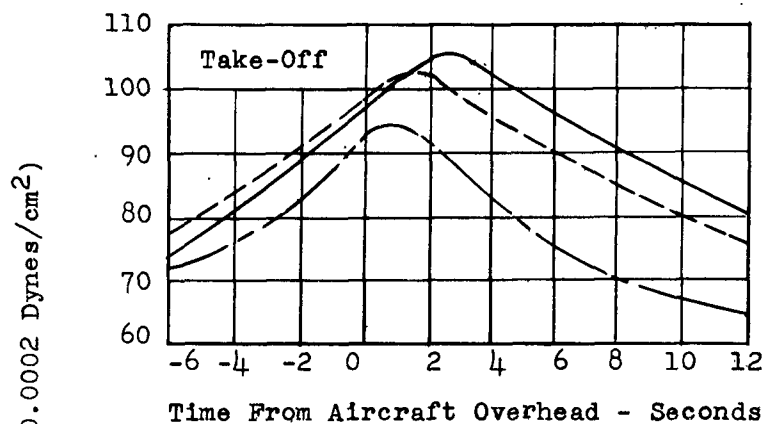
Power Levels for Various Acoustic Sources

Figure 5



Sound Pressure Levels as Function of Wake Velocity for Various Aircraft Noise Sources
Figure 3

	<u>Take-Off</u>	<u>Approach</u>
--- Constellation L049 (Wright Cyclone 745)	2400 RPM/40 in. Hg.	2400 RPM/17 in. Hg.
— Comet 2 (Avon Turbojet 7000 lb. Thrust)	5000 lb. Thrust	1600 lb. Thrust
--- Viscount 701 (Dart Turboprop 1400HP @ 14,500RPM)	13,600 RPM	11,000 RPM



Variation of Noise From Aircraft Passing
500 Ft. Overhead on Take-Off and Approach

Figure 7

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III. AERODYNAMIC NOISE GENERATION AND CONTROL

1. Turbojet Engine Noise Sources

In developing turbojet engines to meet the steadily increasing demands for higher propulsive forces, the engine designer has been introducing additional problems with regards to the noise generation characteristics of the engine. The noise levels have reached values where protective measures must be taken to prevent loss of hearing and other physical damage to personnel in the vicinity of jet engine operation.

The noise developed by turbojet engines is generated primarily by aerodynamic means and is usually referred to as AERODYNAMIC NOISE. Aerodynamic noise differs from other types of noise in that it is not generated by the movement of a rigid surface but rather by the action of an unsteady flow of fluid. Examples of aerodynamic noise generators are vortices, boundary layers, wakes, and jet streams.

While investigators (7, 8, 9) have found that the exhaust jet streams are the predominant noise source of turbojet engines, a portion of the total noise generated can be attributed to such secondary sources as the inlet, compressor, turbine, and combustion chamber. Unfortunately, there are little noise data available to bear out the relative roles of these secondary sources.

The characteristic whine of the compressor is a result of the siren-like effect created as air flows past the compressor blades. At low engine power settings, the compressor noise becomes predominant and is evident as a peak in the high frequency band of the engine noise spectrum (see Figure 26a). This noise is radiated forward of the engine and consists primarily of frequencies above 2000 cps. Above about 85 percent maximum rpm, noises generated by the compressor become masked by the intense noise generated by the jet exhaust. Compressor noise has been difficult to correlate since it appears to be a function of several factors such as horsepower, shaft speed, number of blades, number of stages, and flow capacity. The peak spectrum, which is characteristic of compressor noise, appears to be a function of the relative speed of the rotor and of the number of blades, while the intensity of the generated noise appears to be a function primarily of the horsepower delivered to the compressor; in fact, the limited available data indicates that a doubling of horsepower produces approximately a 6 db increase in the total acoustical power generated by the compressor. Prediction of jet engine compressor noise has been based upon theory and design procedures used in estimating propeller noise because of the acoustic similarity between these two sources (7).

Noise generated in the combustion chamber is believed to be the result of unstable burning of the gases and of vibration of the combustion chamber walls. Full-scale engine tests indicate that rough burning increases the noise level considerably (10). Noise data also seems to indicate that stationary waves are generated in annular type combustion chamber passages; these waves generate the characteristic high intensity, low frequency noises associated with annular combustors.

Although these secondary sources do not contribute much towards the total noise levels of present-day turbojet engines, it is conceivable that with the advent of larger powerplants, with transonic or supersonic compressors, and with the development of more effective jet noise reduction devices, these secondary sources may become of primary concern. Also, present ground run-up operations to check out equipment and engine controls are usually performed at the low rpm settings where compressor noise is predominant.

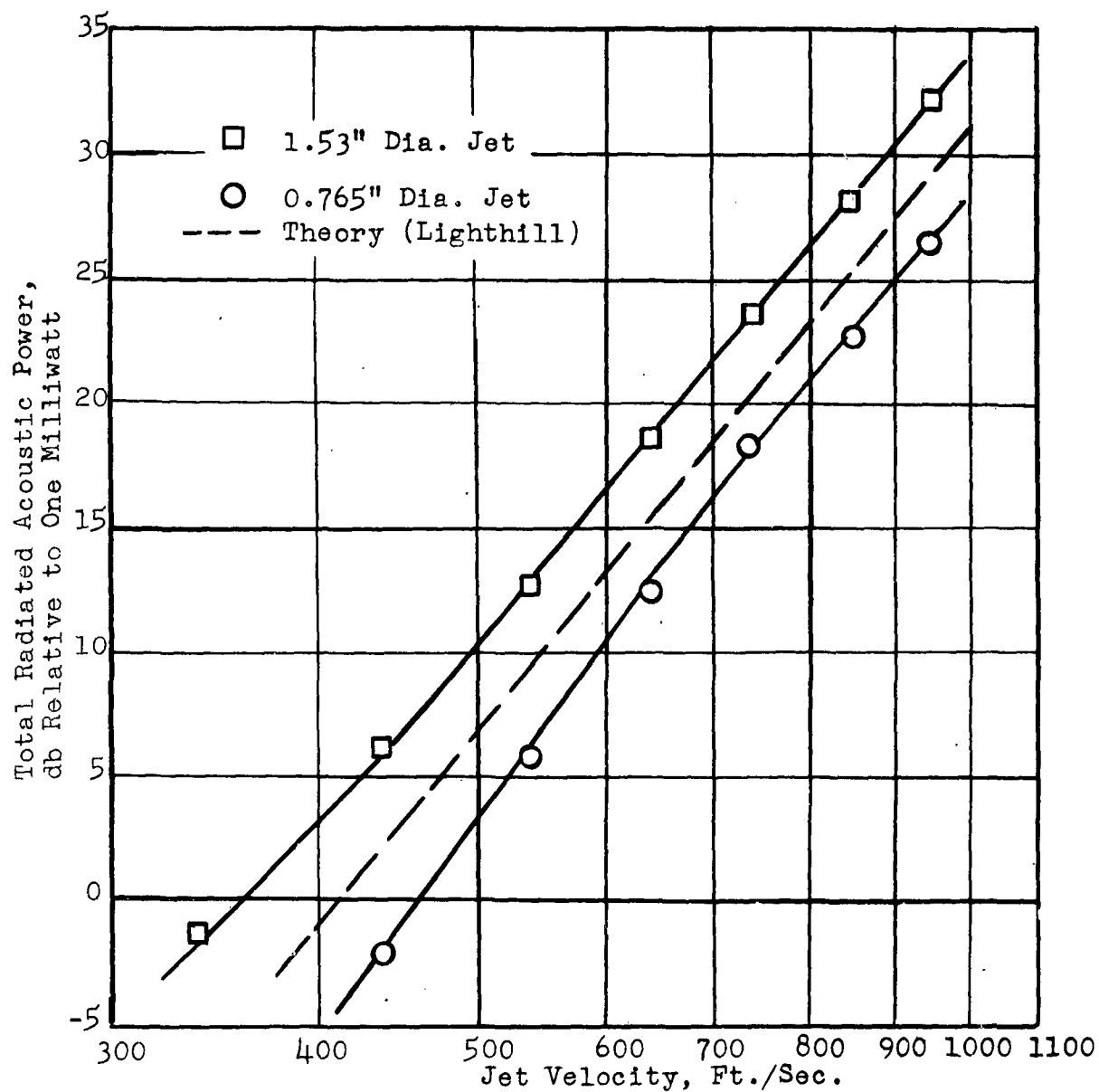
To date, the major efforts in the field of aerodynamic noise generation and control can be associated with jet noise studies. The problem of jet noise generation and propagation in turbojet engines has received extensive theoretical and experimental consideration; this could be attributed perhaps to a jet nozzle's more obvious role as a noise generator compared to the other noise generating components of a turbojet engine. In concentrating their efforts on jet noise, investigators have been able to assemble sufficient noise data to bear out the major role of jet nozzles in the field of aerodynamic noise generation.

2. Exhaust Jet Noise - Subcritical Flow

Lighthill's Theory

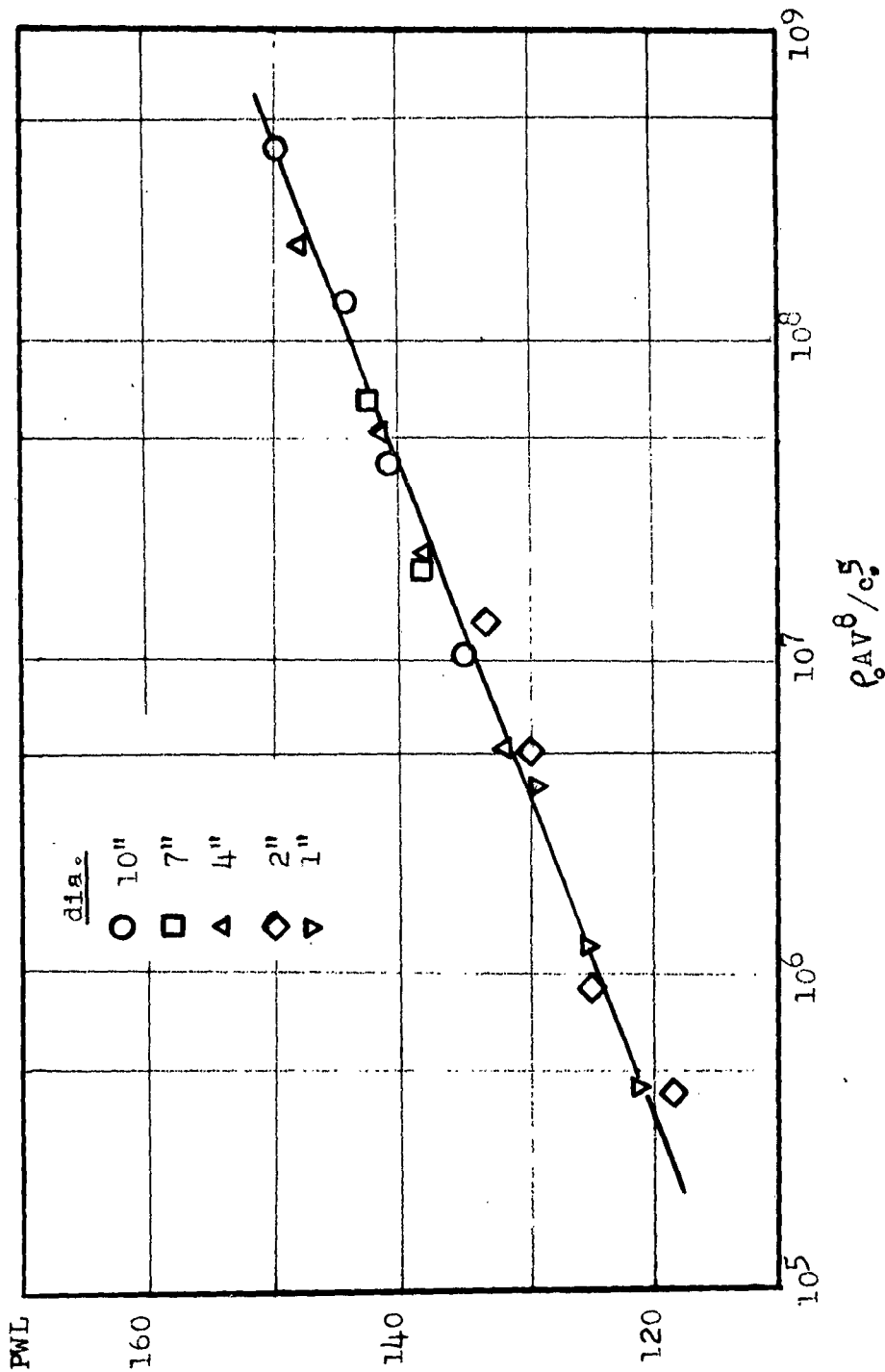
Exhaust nozzles, developed primarily for efficient conversion of pressure energy to kinetic energy so as to produce maximum jet engine thrust, have become the subject of intensive studies because of their supplemental role as noise generators. Recent experimental efforts by several investigators, both in this country and abroad (11, 12, 13, 14, 15, 16) have established that the aerodynamic phenomenon, jet noise, is primarily a result of turbulent mixing of the jet stream with the surrounding atmosphere. It is of interest that experimental data has correlated (within the limits of experimentation) with a theory developed by Lighthill for subsonic flow. Previous to Lighthill's analytical examination of the mechanism of aerodynamic jet noise generation, scientists in the field of acoustics had the ability to observe only the effects of jet noise. Lighthill's work made it possible for investigators to understand jet noise phenomena.

By employing the concept of an "acoustic quadrupole" as the elementary sound generator, Lighthill was able to show mathematically that the total acoustical power, radiated by a jet discharging into quiescent air, varies directly as the eighth power of jet exit velocity and the second power of the jet exit diameter. Recently, investigators (8, 9, 17, 18) have been able to confirm this experimentally for both scale-model jets and full-scale turbojet engines (Figures 8, 9, 10, 11). Lighthill's initial analysis (1-1) presented a tensor expression which related the noise intensity to the shearing stresses of the fluid. The analysis assumed a cold flow at subsonic conditions and a fixed distribution for the acoustic quadrupole sources. The quadrupoles represent the molecules of the fluid. The radiation pattern of Lighthill's acoustic quadrupole was directional, having a four-lobed clover leaf pattern with maxims at an angle of 45° to the jet axis. Unlike simple sound sources, jet noise is highly directional and similar to that predicted by the quadrupole concept. Of the three theoretical sources of aerodynamic noise, monopole, dipole, and quadrupole, the latter is the only one which is applicable to jet noise theory since its sound generation is produced by the action of shear and moments upon the fluid system. Where a fluid is emitted periodically as in a pulse jet, the theoretical approach to noise generation is based upon a monopole source. Propeller noise theory has been successfully based upon the dipole source as the noise generator since this source represents a periodic force in a free fluid - the same physical action which occurs on propeller blades. Of the three sources, the quadrupole source is the least efficient acoustic generator, converting only 1/1,000 as much of its kinetic energy to sound energy compared to a monopole source. Lighthill's theory showed that the



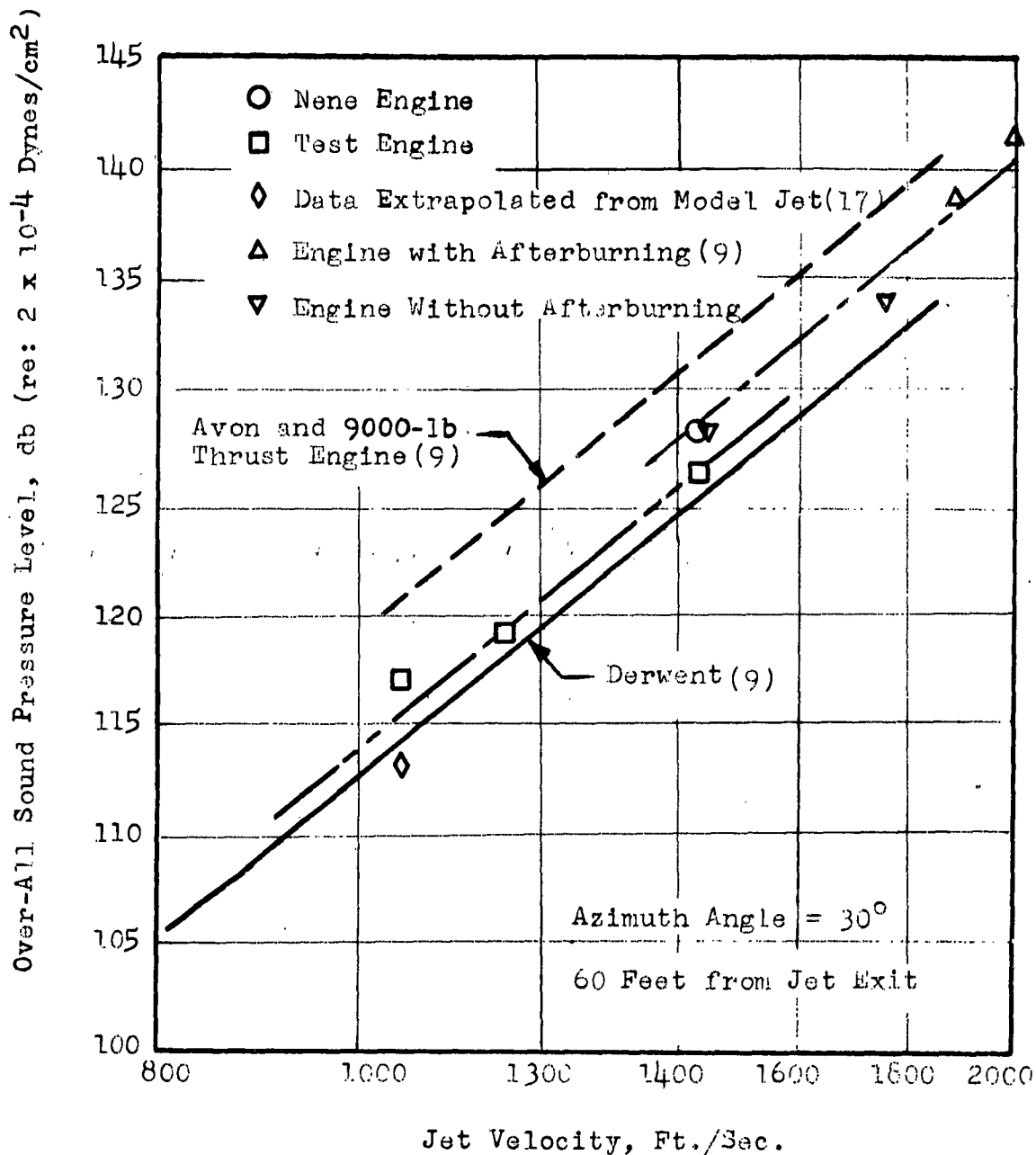
Total Acoustic Power Radiated by Two
Subsonic Air Jets as a Function of Jet Velocity

Figure 8



Bellmouth Nozzle Power Level^{8/5}
Vs. Lighthill's Parameter, $\rho AV^8/c_s^5$

Figure 9



Over-All Sound Pressure Level Vs. Jet Velocity
for Several Different Jet Engines

Figure 10

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efficiency of this conversion is proportional to the fifth power of Mach number with only minor dependence upon Reynolds' number. Experimental data (19) shows that the proportionality constant for this conversion is approximately 10^{-4} for subsonic flow. Thus, the above relations can be expressed as follows:

$$\eta = 10^{-4} M^5 \frac{\rho_0}{\rho} \quad (IV)$$

$$\text{and Total Acoustic Energy} \propto \frac{\rho_0 V^8 d^2}{c_0^5} \quad (V)$$

where η = efficiency of converting kinetic energy to acoustical energy

M = jet Mach number

ρ = jet density

ρ_0 = density of surroundings

c_0 = velocity of sound in surroundings

V = jet velocity

d = jet diameter

Thus, for a cold jet having an exit Mach number of 2.0, the energy conversion is approximately 0.3 percent, while for lower exit Mach numbers, i.e., 1.0, the conversion is reduced to approximately 0.01 percent. Figure 12 shows typical values of kinetic energy associated with various propulsion systems.

However, Lighthill's theory of jet noise generation is not yet complete despite correlation of experimental data (Figures 8, 9, 10, 11) with his $\frac{\rho_0 A V^8}{c_0^5}$ expression. A second

paper by Lighthill (1-II) raised the question of the validity of his initial assumption of a fixed distribution of acoustic quadrupoles. If there is a quadrupole convection effect, i.e., a moving distribution of quadrupoles, the total acoustical power generated by a jet should be proportional to a higher exponent of jet velocity than the eighth power.

The Noise Fields

The acoustical energy radiated by an aerodynamic source, such as a jet nozzle, spreads as it propagates in the surrounding atmosphere in a quasi-axially symmetric manner. The noise from the jet is a result of turbulent mixing in the wake which begins close to the jet exit. This mixing region progresses downstream, spreading throughout the flow. Several diameters downstream from the jet exit, the turbulent mixing region completely penetrates the core of the jet, and it is found that the sound energy propagates in a manner similar to that for light, viz., according to the inverse square law. (The acoustical power per unit area decreases as the square of the distance from the noise source.) This region is known as the "far field." References in the field of acoustics state that for a plane or spherical sound wave emanating from a uniformly generating source, sound intensity can be expressed as:

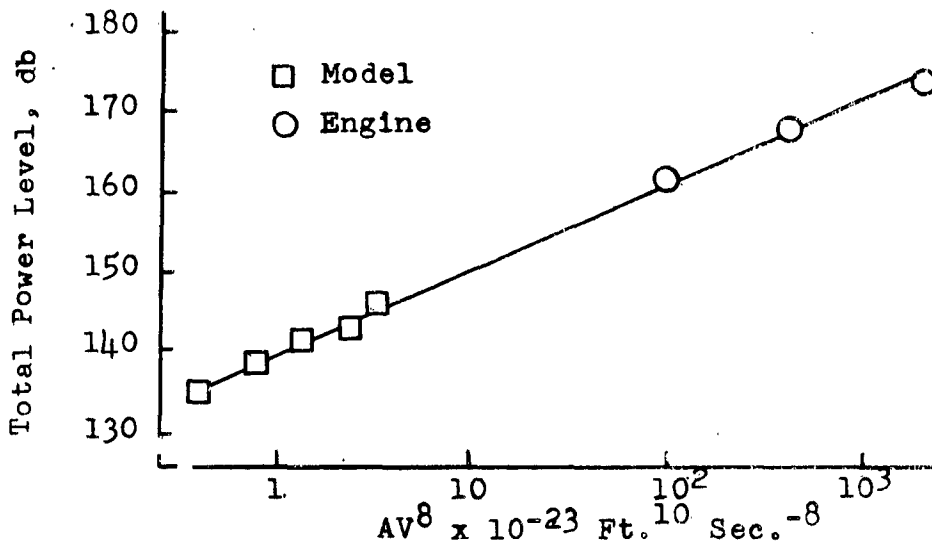
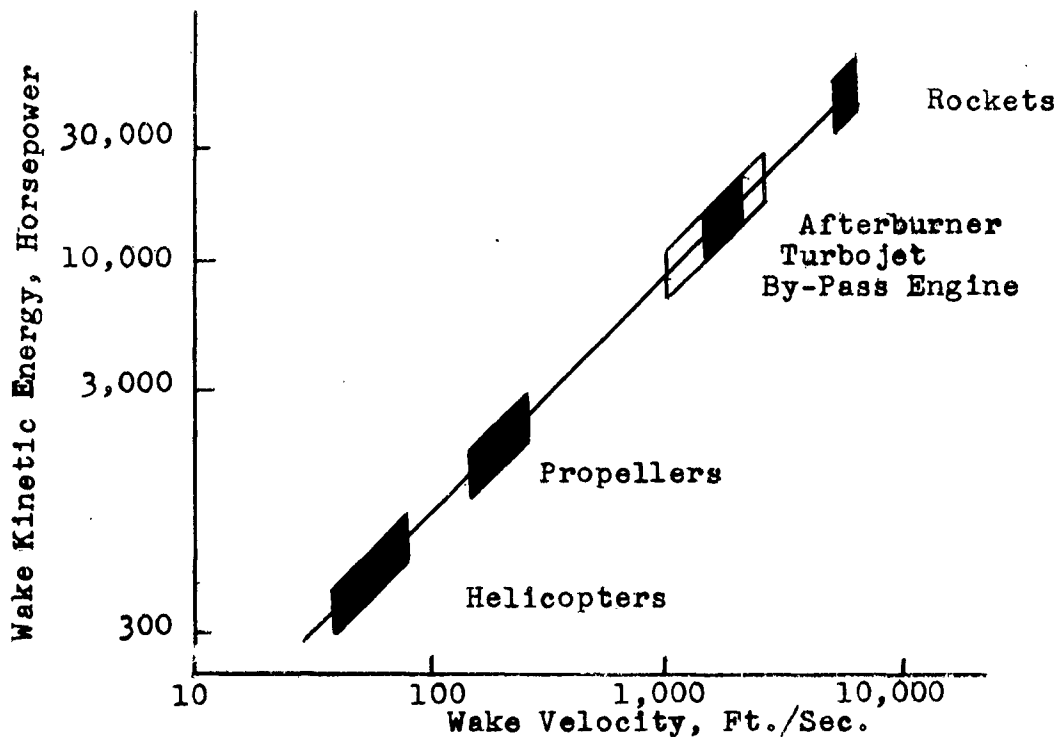


Figure 11. - Total Power Level as a Function of AV^8



Kinetic Energy in Wake to Produce
10,000 Pounds of Static Thrust for
Various Aircraft Propulsive Systems

Figure 12

$$I = \frac{p^2}{\rho_0 c_0} = \frac{W}{A} \quad (VI)$$

where W = sound power
 p = sound pressure
 A = area through which sound is transmitted

Substituting this relation in the equation for sound power level, $PWL = 10 \log_{10} \frac{W}{W_0}$, the following expression can be obtained:

$$PWL = 10 \log_{10} \frac{IA}{I_0 A} = 10 \log_{10} \left(\frac{p}{p_0} \right)^2 \quad (VII)$$

Although the noise generated by a jet is not uniformly symmetric, the above relations are still applicable; acoustic power is then approximately proportional to the square of the sound pressure. From the inverse square law, the following relation can also be obtained:

$$W \approx \frac{1}{(\text{Distance})^2} \approx p^2 \quad (VIII)$$

or

$$p \approx \frac{1}{(\text{Distance})}$$

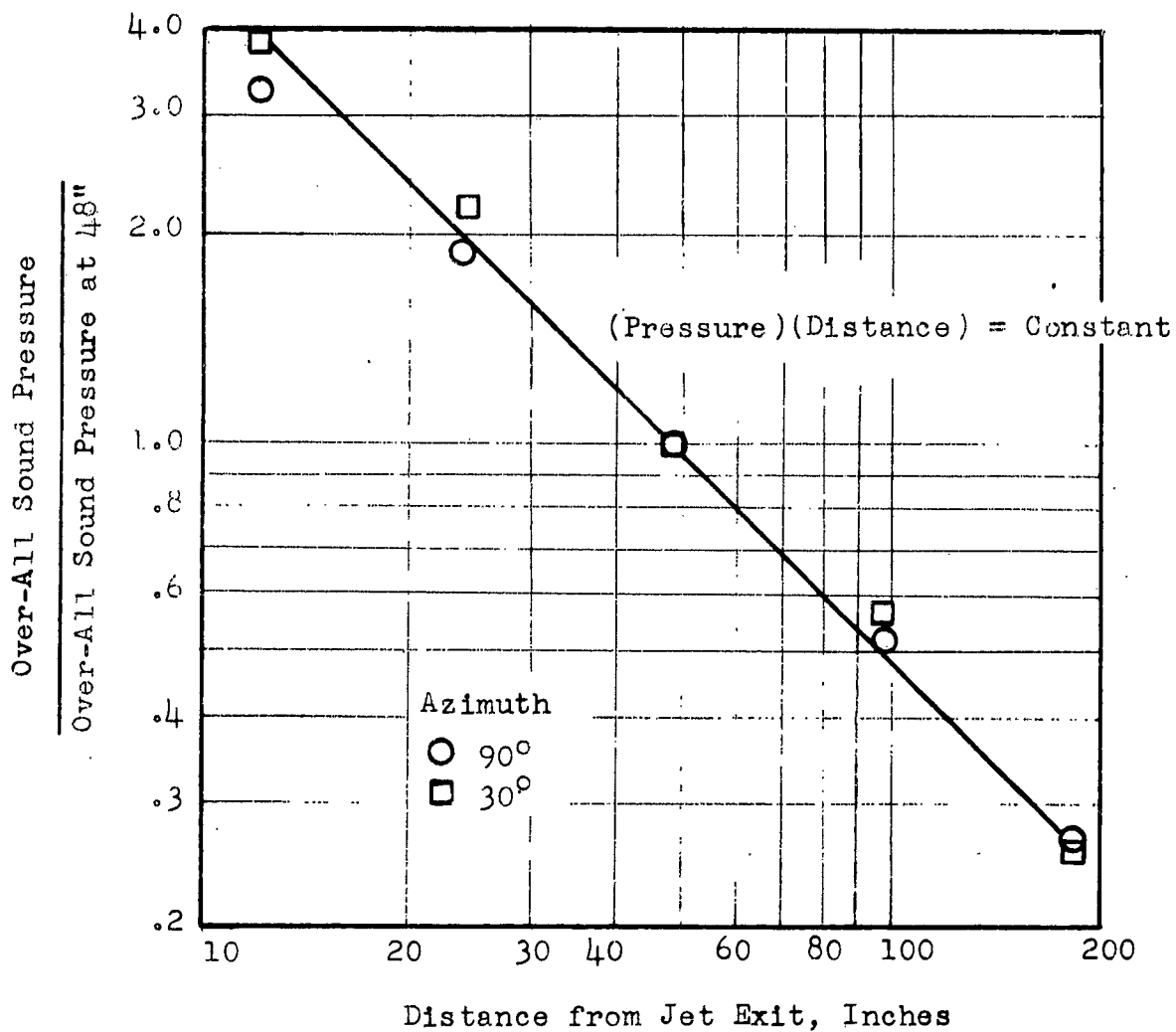
Utilizing the sound pressure level expression (I) and the above relation

$$\Delta \text{ SPL} \approx -20 \log_{10} \frac{(\text{Distance} + \Delta \text{Distance})}{(\text{Distance})} \quad (IX)$$

Thus, if the distance from the noise source is doubled, a 6 db reduction of sound pressure level should occur in the far field for choked or unchoked jets. Figure 13 shows actual measurements taken in a far field.

Between the nozzle exit and the far field region lies the "near field" in which the sound distribution is noticeably different from the case of the far field. In this region, jet noise is propagated in a manner which does not follow the inverse square law but some complex relation which is still the subject of investigations. While neighborhood complaints to jet engine noise are a result of far field noise levels, the pernicious effects of jet noise are evidenced in the near field where the pilot, passengers, and service crews are located, and therefore it is essential to intensify research efforts in this area.

The presence of thermal currents, winds, and obstacles (i.e., terrain, structures, etc.) affect the propagation of jet noise in the distant far field. Thermal currents cause sound waves to bend so that they follow a curved path, bending in the direction away from the higher temperature strata and towards the lower temperature strata. The result of these sound diffractions is the formation of "shadow zones" through which very little sound propagates. Moreover, some of the sound energy is absorbed by the atmosphere during propagation,



Effect of Distance on Over-All Sound Pressure
from Air Jets (V = 1000 Ft. Per Second)

Figure 13

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particularly the high frequency portion of the sound spectrum (see Figure 14). Absorption, reflection, and scattering of directed sound occur when sound waves strike obstacles. These factors influence the response of a community to jet engine noise.

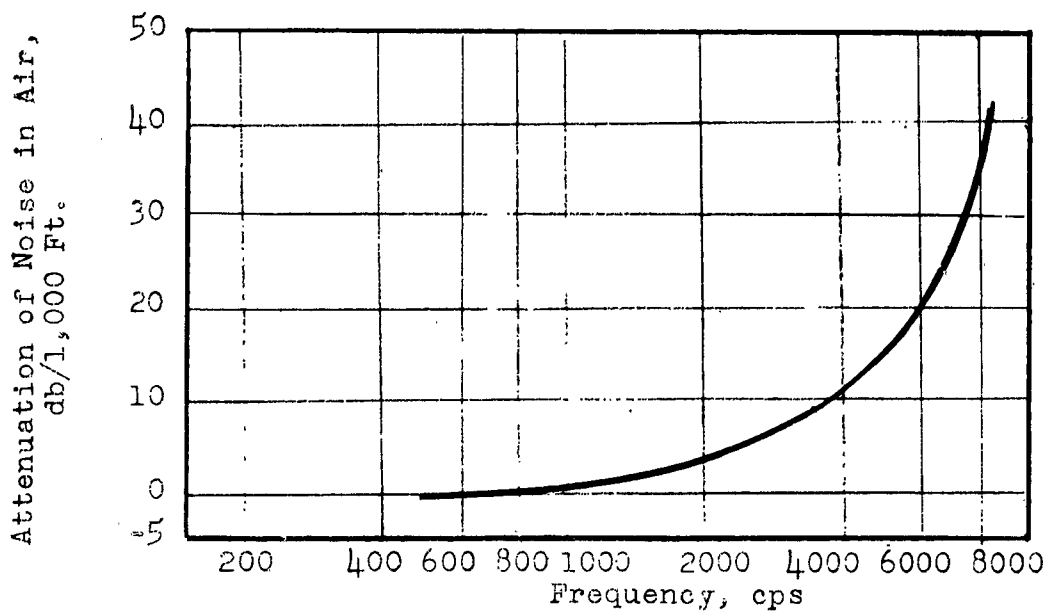
Noise due to turbulent mixing of a subsonic jet is characterized by its having no discrete frequencies and having some randomness of sound pressure amplitude. The spectrum extends over many octaves in frequency and has a broad maximum as evidenced from Figure 15. Propeller noise which is found to be most intense near the plane of rotation has the characteristic that the maximum sound pressure level is located in the plane of propeller rotation, especially for high tip speed propellers. Jet noise, however, has a maximum sound pressure level to the rear of the engine and positioned along a 30° azimuth from the jet axis. For unchoked operation of turbojet engines, frequencies of about 200 to 1500 cps occur near the jet axis. At about two diameters downstream from the jet nozzle exit, the predominant frequencies range less than 200 cps. While the frequency content of the turbojet engine can extend to about 10,000 cps (within the audible range), the higher frequencies contain little acoustical energy.

Model and Full-Scale Jet Noise Data

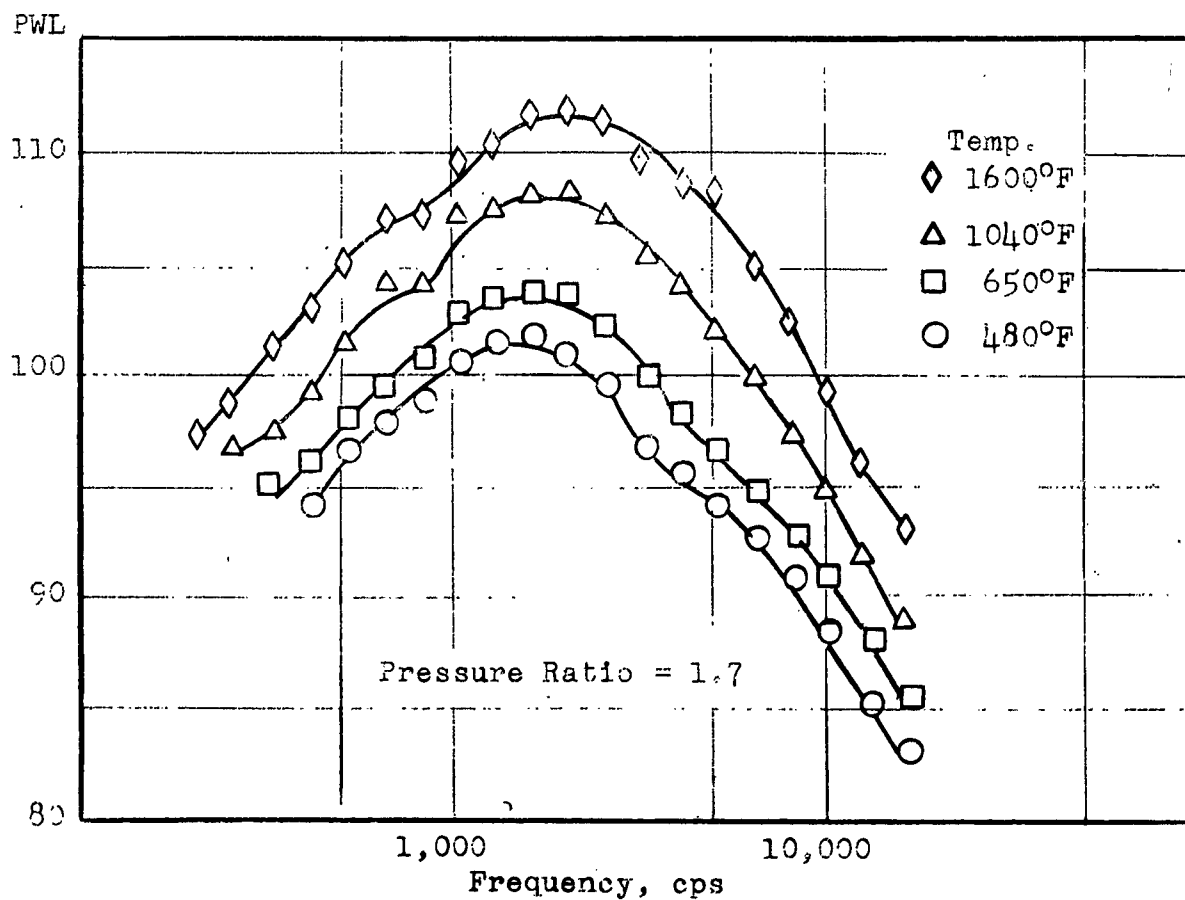
Subsonic experimental data indicate that the noise generated by full-scale turbojet engines is governed by the same laws as the simple air jet, and implies, therefore, that turbulent mixing of the jet with the atmosphere is the major source of jet engine noise. For the same jet velocity, both model and full-scale engine jet nozzles produce approximately the same sound pressure level at similar values of (distance from jet exit/jet diameter). This relationship is shown in Figure 16. These tests also indicate that sound pressure appears to vary directly as the (jet velocity)⁴ in the far field region, thereby agreeing with Lighthill's expression for jet noise. Both model and full-scale jet engine tests illustrate and corroborate Lighthill's theoretical conclusions that jet noise is also proportional to the square of the jet diameter. The tests indicate that decreasing the nozzle diameter reduces the total acoustical power generated by the jet, but also causes the noise spectrum to shift towards the higher frequency bands. (See Figure 17.) Several investigators have attempted to estimate this shift in the peak value of the noise spectrum by the use of a dimensionless parameter, the Strouhal Number, where:

$$\text{Strouhal Number} = \frac{(\text{peak frequency})(\text{jet diameter})}{(\text{jet velocity})} \quad (X)$$

From numerous measurements of full-scale turbojet noise data, it has been found that Strouhal Number $\approx 0.13(20)$. Thus, if jet diameter and velocity are known, it is possible to predict the frequency peak in the spectrum for full-scale engines, by

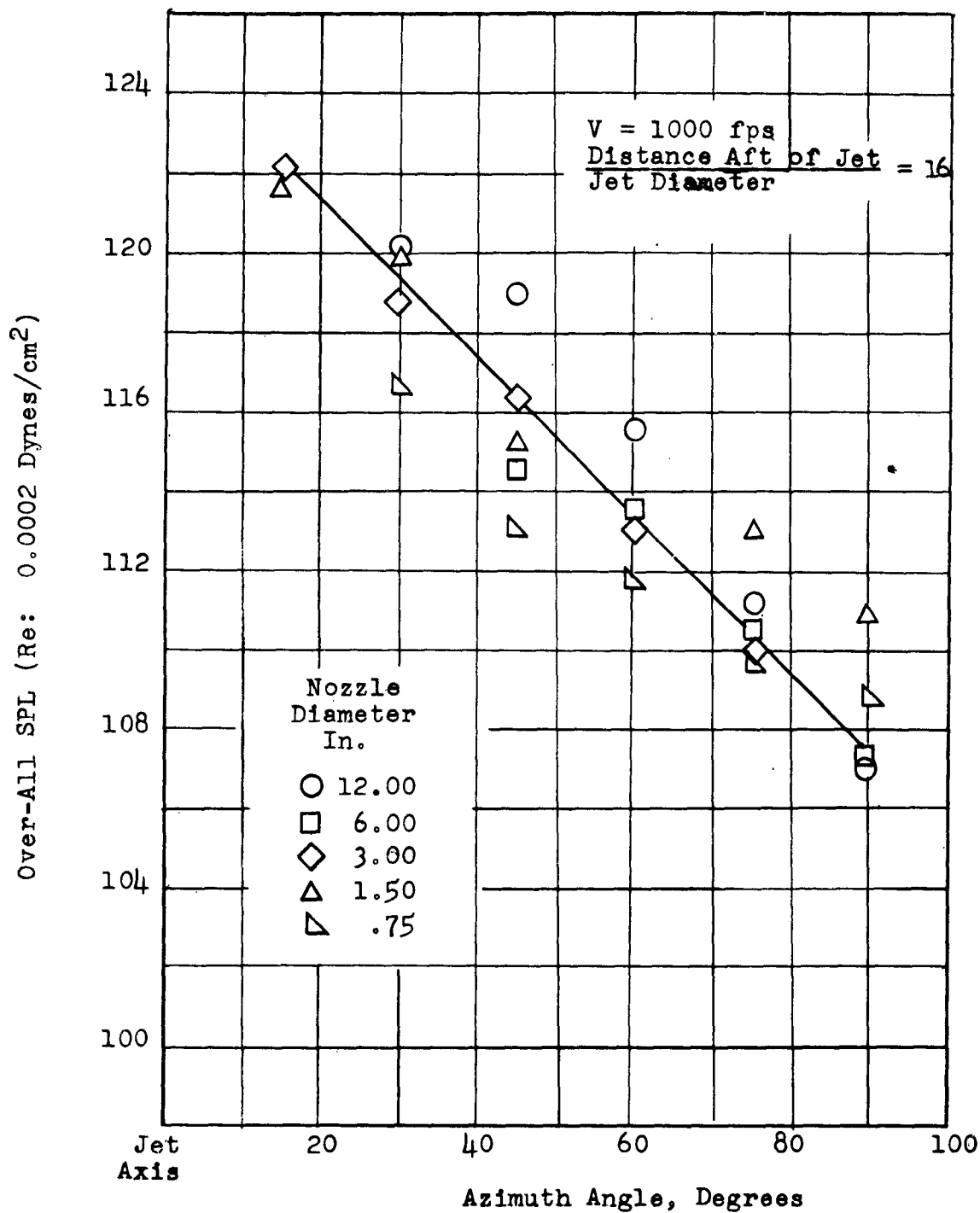


Atmospheric Absorption of Noise
Figure 14



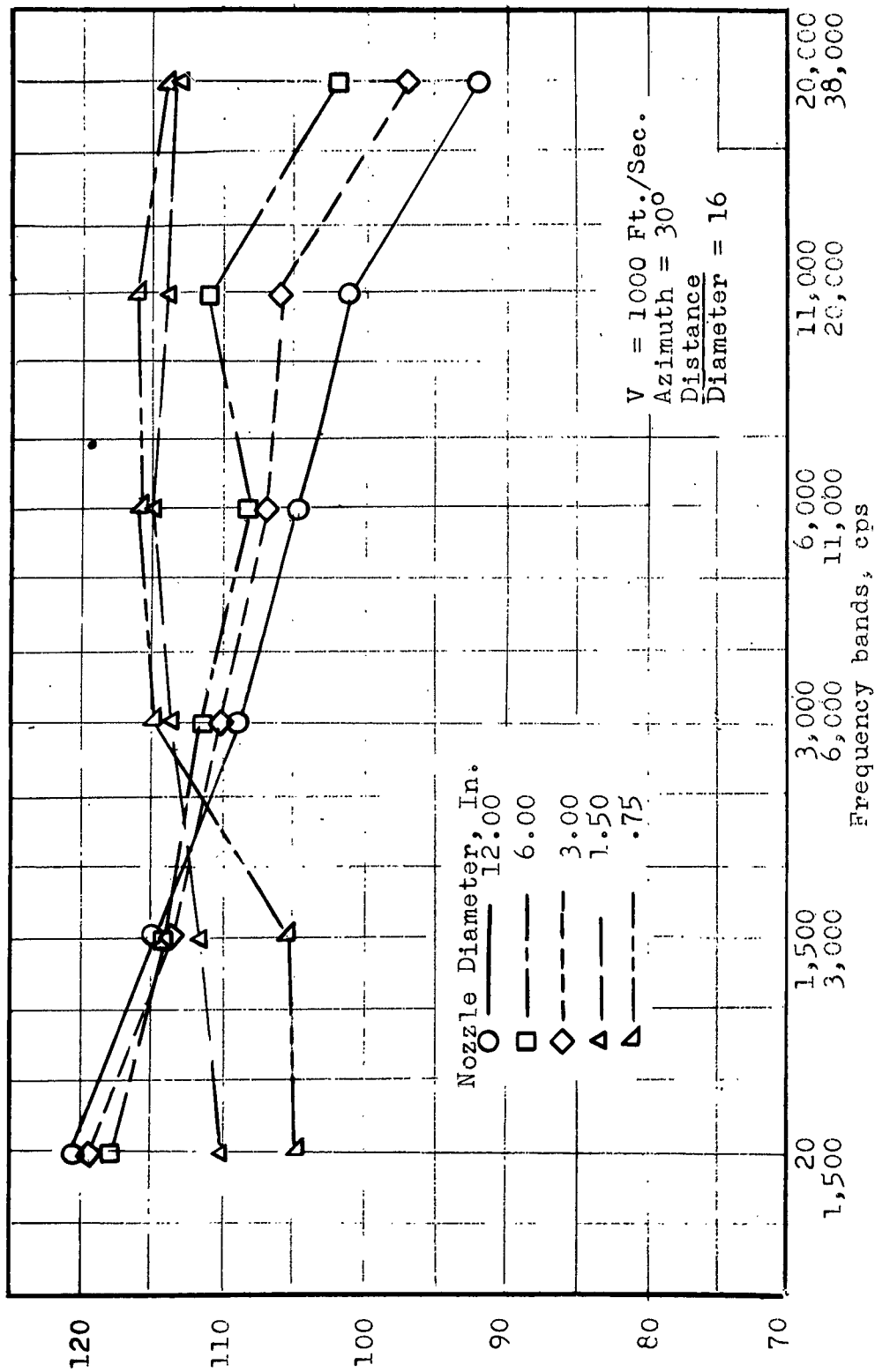
The Effects of Temperature on the Power Spectrum
From a Conical Nozzle at Subcritical Pressure Ratio

Figure 15



Effect of Azimuth Angle and Jet Size on the Over-All Sound Pressure Generated by Air Jets

Figure 16



Effect of Nozzle Size on Air Jet Noise Spectrums

Figure 17

use of the above value for Strouhal Number. The existence of a relationship between Strouhal Number and Reynolds' Number could help to establish a method of predicting the position of the peak in the full-scale engine noise spectrum from model test data. This subject requires further study.

Although disagreement exists among a few investigators concerning the relationship between acoustic power generation and fluid flow parameters, a preponderance of test data appears to substantiate use of Lighthill's eighth power velocity relationship. One of the significant facts obtained from these research investigations has been that turbojet engine noise data, at rated power, falls on the same curve as model jet data even though the gas temperature differs between the two tests by as much as 1,000°F. Evidence of this fact is shown in Figures 10 and 11. The effect of increasing temperature upon sound power level while maintaining a constant jet pressure ratio is illustrated by Figure 15. Jet velocity increases as a result of increasing gas temperature, consequently, the total generated acoustic power increases. Note that as the jet velocity increases, the maximum sound power level and its frequency increase, also. Similar test data are shown in Figures 18, 19, and 20. The data indicate that two identically sized jets, operating under different pressure ratios and temperatures but having the same jet exit velocities, will generate nearly the same acoustical power. It appears, therefore, that jet velocity is the most important parameter contributing towards the generation of jet noise.

Perusal of available noise data reveals a lack of information concerning the effect of the cone half-angle of the nozzle on the generated noise. A report written by Tyler and Perry (21) states that the power spectrum is independent of the angle of convergence, while their data (Figure 21) indicate a difference of approximately 3 db between a convergent nozzle of 15° wall angle and a flat plate orifice (90° convergence angle) having the same physical throat size. Since for the same physical throat size a flat plate orifice has a lower discharge coefficient, the actual jet area for a particular pressure ratio would be less than that of a nozzle with a smaller convergence angle. Therefore, the generated acoustic power for a flat plate orifice should be less than that for nozzles with smaller cone half-angles. This trend is indicated to some extent by the above data although the 3 db reduction is probably in the range of test accuracy. Also power level reductions on this order are insignificant; 10 to 20 db reductions are required to relieve excessive noise levels at the present time.

Examination of model and full-scale engine test data (unchoked flow conditions) reveals that each frequency band of the generated noise spectrum has a different propagation direction; in general, the lower frequency bands are located downstream near the axis of the jet, while the higher frequency

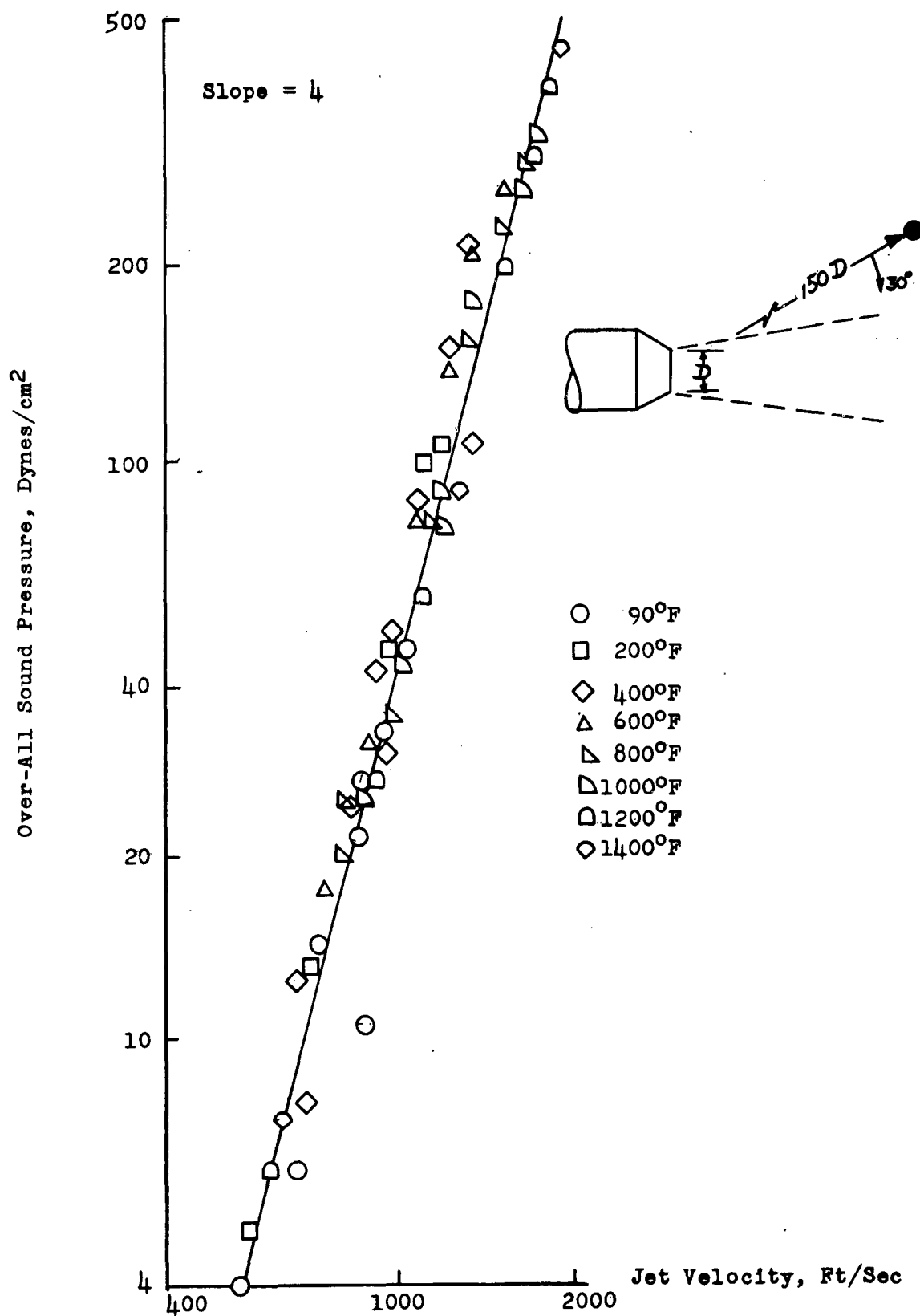
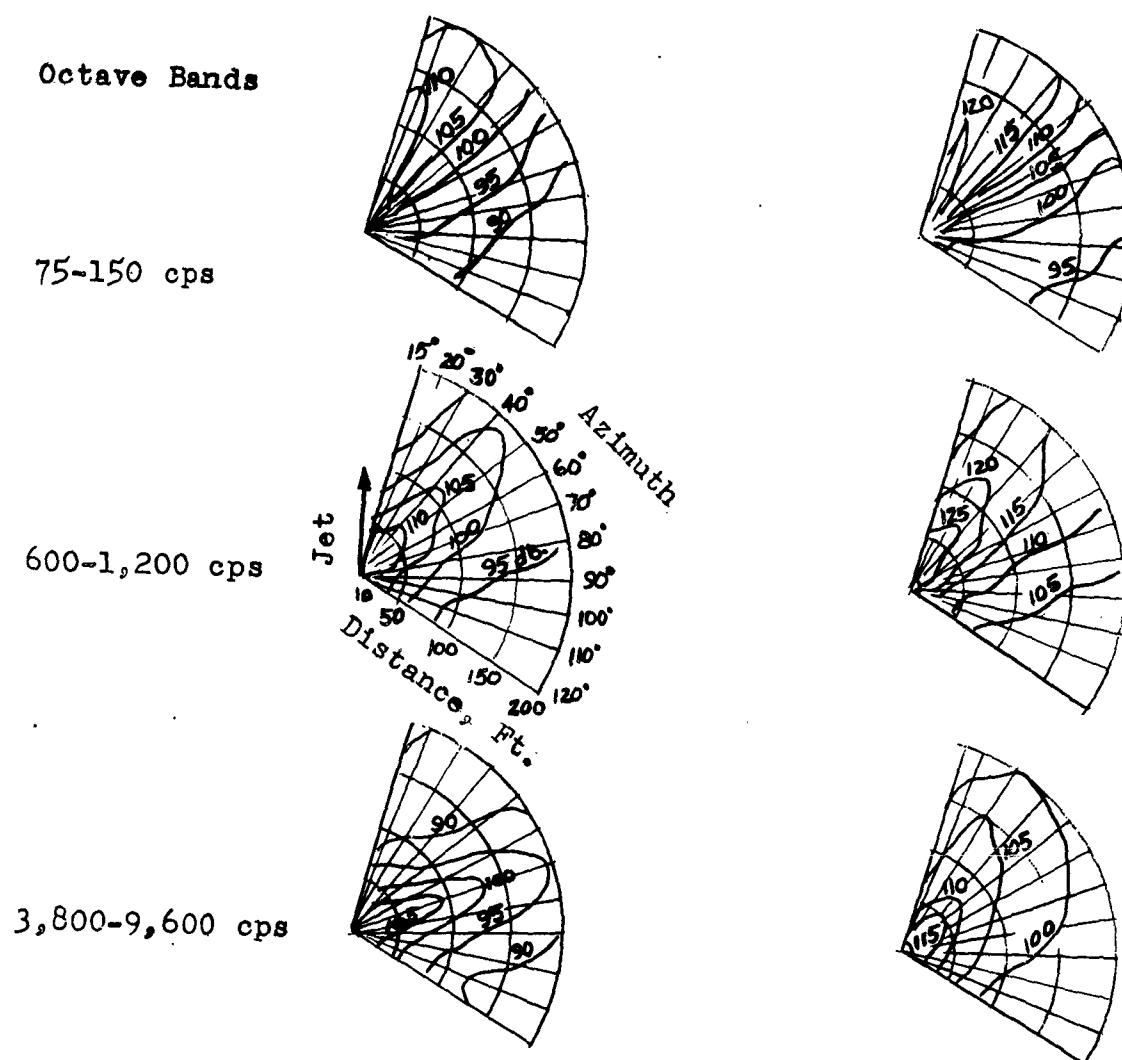


Figure 18. - Sound Pressure at a Distance of 150 Diameters
For a Jet Operating at Various Temperatures

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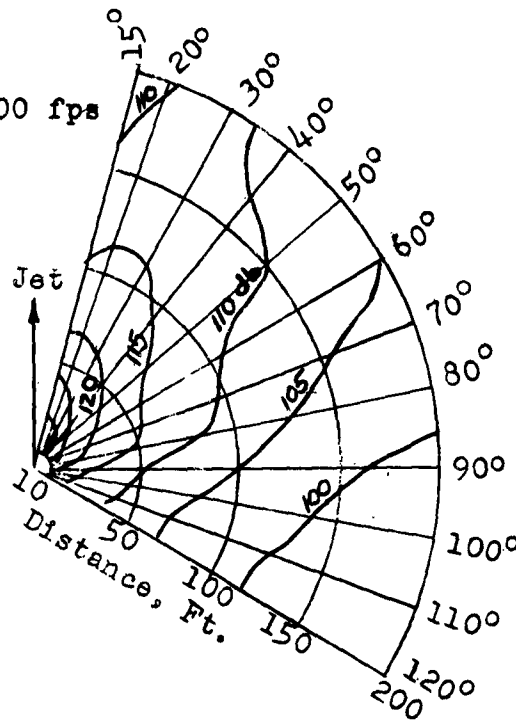


Jet Velocity = 1300 Ft./Sec. Jet Velocity = 1800 Ft./Sec.

Avon Engine Noise Level Contours

Figure 19

Jet Velocity = 1300 fps



Jet Velocity = 1800 fps

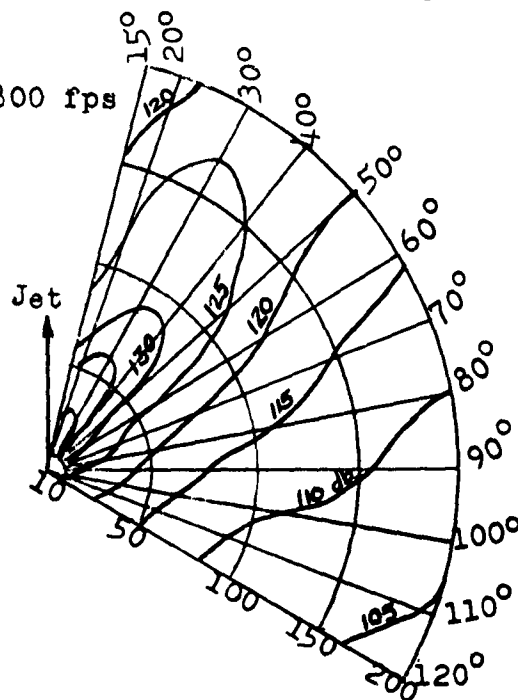


Figure 20. - Total Noise Level Contours for Avon Engine

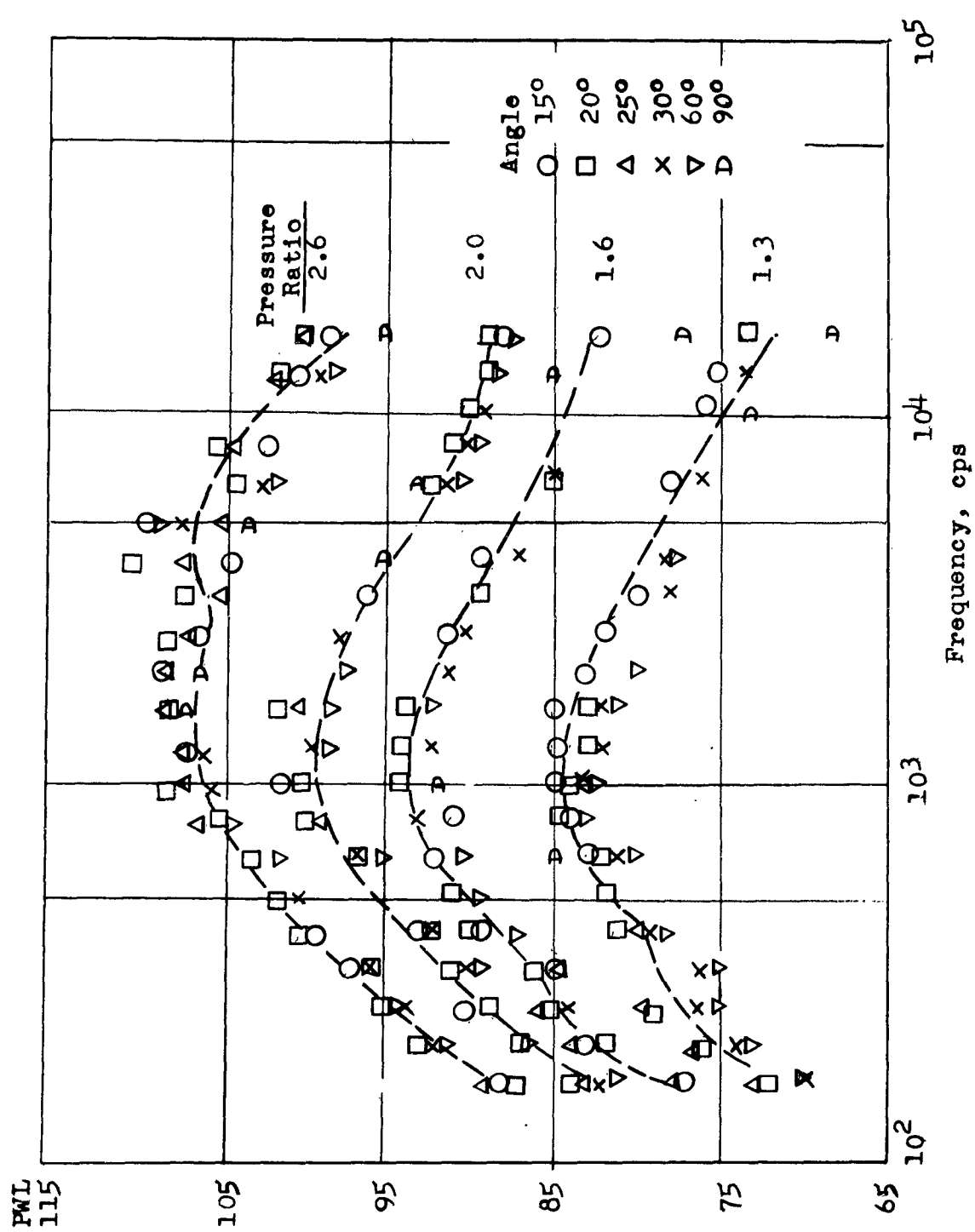


Figure 21

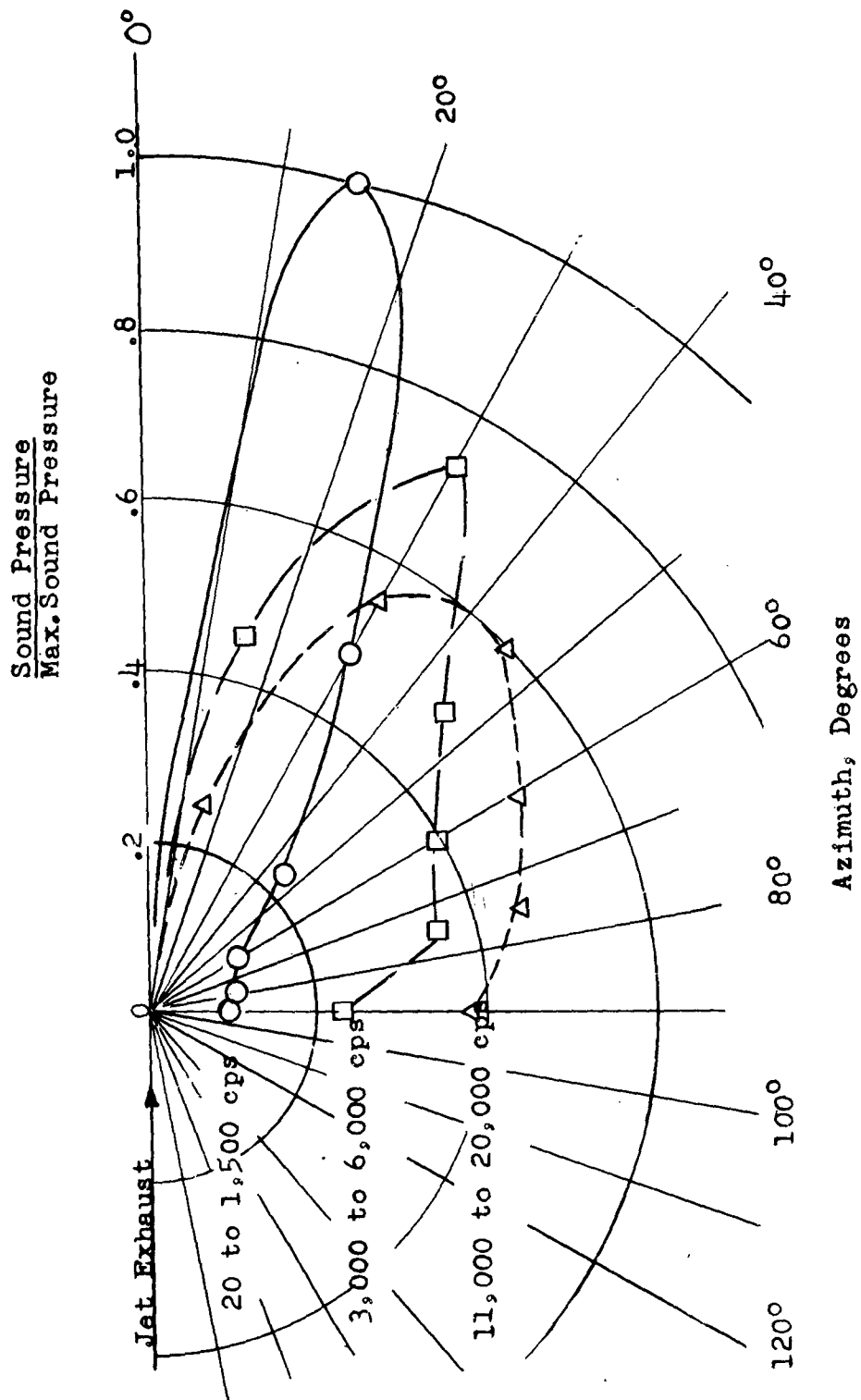
bands are located at larger angles to the jet axis and appear to emanate from a region close to the jet nozzle exit (Figures 19 and 22). The intensity of these bands varies with azimuth angle and velocity. The angle of maximum intensity increases with jet velocity as evidenced by those data (Figures 19 and 20). It is believed that the angle of maximum sound radiation is greater at high velocities because increasing the jet velocity raises the frequency of the maximum component of the noise spectrum. Since higher frequencies are located away from the jet axis, the angle of maximum intensity becomes larger. Powell (22) believes that the higher frequency sounds are generated, particularly in the annular shear layer of the jet, by lateral quadrupoles and that the lower frequencies are generated by omnidirectional sources farther downstream.

Noise data of turbojet engines operating under afterburning conditions indicate that higher noise levels are generated primarily because of the higher jet velocities, increased temperatures, and larger jet nozzle areas involved. Test data gives evidence of the existence of strong resonance conditions at high fuel-air ratios and high jet velocities. Under these circumstances, the resonant frequencies sometimes contribute nearly 50 percent of the total noise energy and have been known to cause structural failure of flameholders (10 and 23). Experimental tests on a fighter aircraft operating with an afterburner (Figures 23 and 24) indicated that maximum sound pressure levels occur at approximately 45° from the jet axis, slightly greater than for non-afterburning turbojet engines.

The above discussion applies to the far field where the generated noise appears to obey the inverse square law and Lighthill's theoretical relationship. In the near field, these relations do not appear to apply and no clear relationship is available at the present time to explain or to relate physical measurements in this noise field.

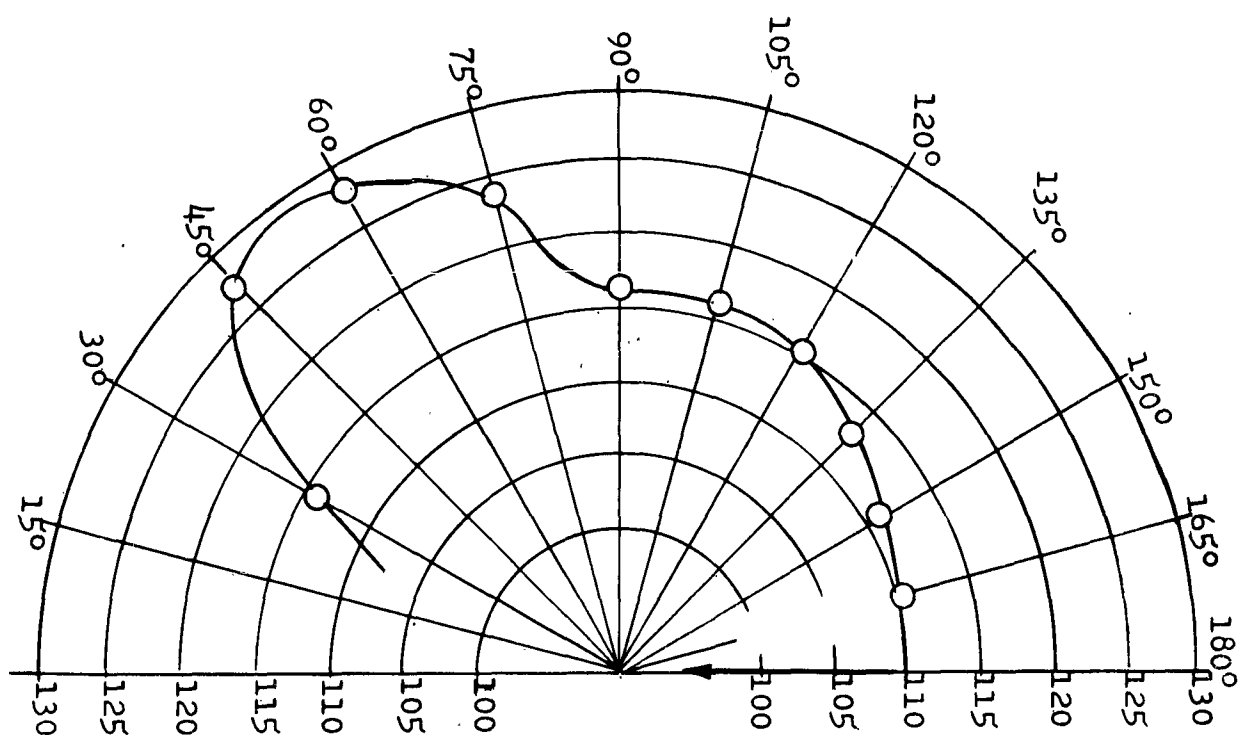
As in the far field region, jet velocity manifests itself as the most important parameter in governing the sound pressure in the near field. While the sound pressure in the far field is proportional to the (jet velocity)⁴, model test data taken in the near field at the nozzle exit and in a plane perpendicular to the model jet axis, indicate that the sound pressure is a function of jet velocity to an exponent which varies from 2 to 4 depending upon the radial distance from the jet (Figure 25). Noise data taken in the near field close to the jet boundary of a turbojet engine (Figure 26) indicated that at distances greater than 15 diameters most of the sound pressure consisted of frequencies of less than 150 cps. The maximum pressure fluctuation occurred between 12 and 15 diameters, while closer to the jet nozzle exit, at about 3 diameters, the pressure fluctuations were mostly in the 2,000 cps frequency range.

The near field noise of a jet engine exhaust has been known to cause fatigue failures of airplane wing or fuselage skin



Polar Distribution of Various Frequency Bands of Noise
Generated by a 1.5-Inch-Diameter Air Jet
($V = 900 \text{ Ft./Sec.}$)

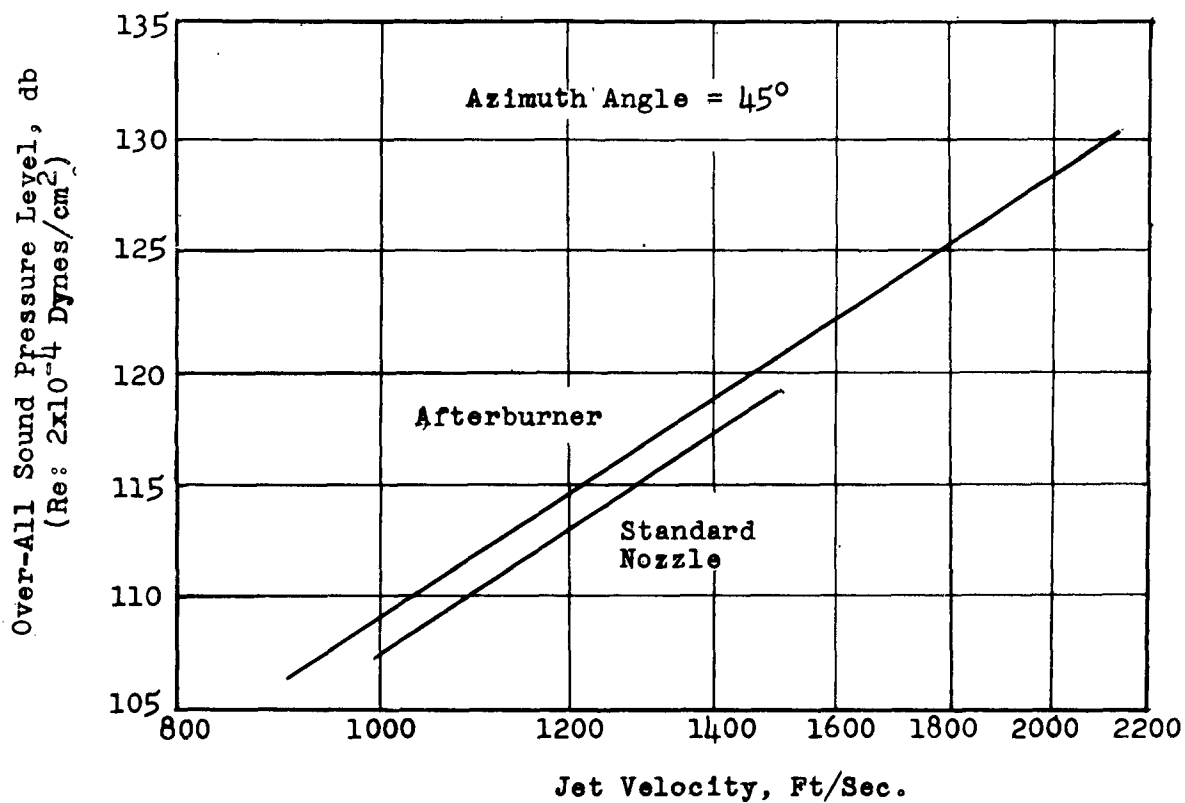
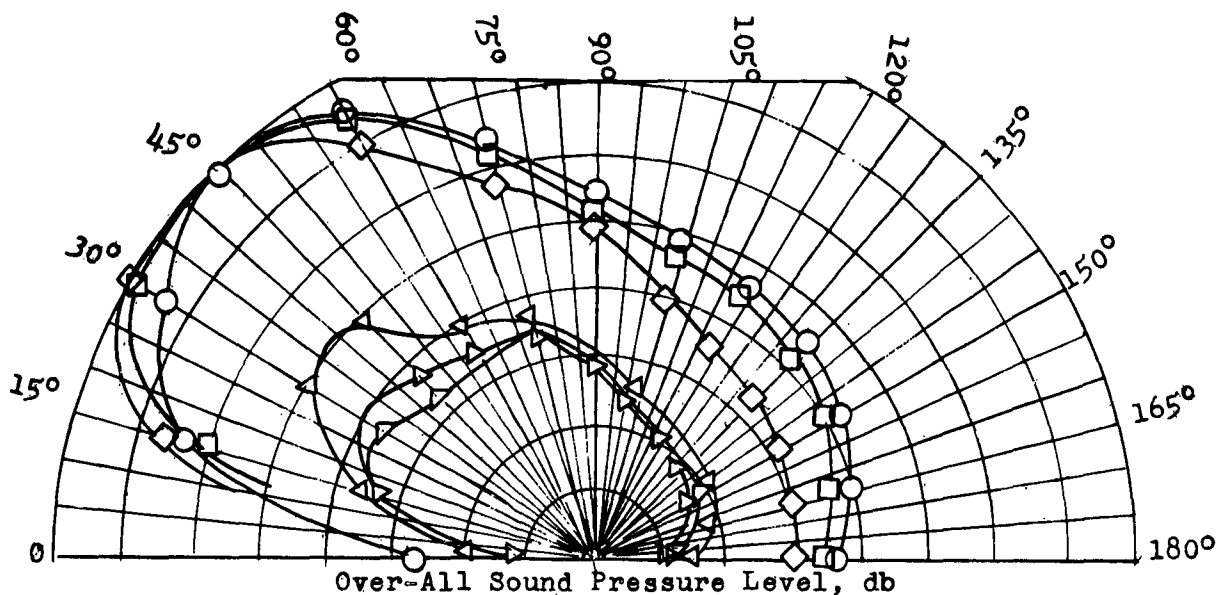
Figure 22



Overall Sound Pressure Level, db.

Polar Diagram of Sound Field For Fighter Aircraft Engine
Installation under Maximum Afterburner Thrust Condition.
(Distance from Jet Exit, 200 feet)

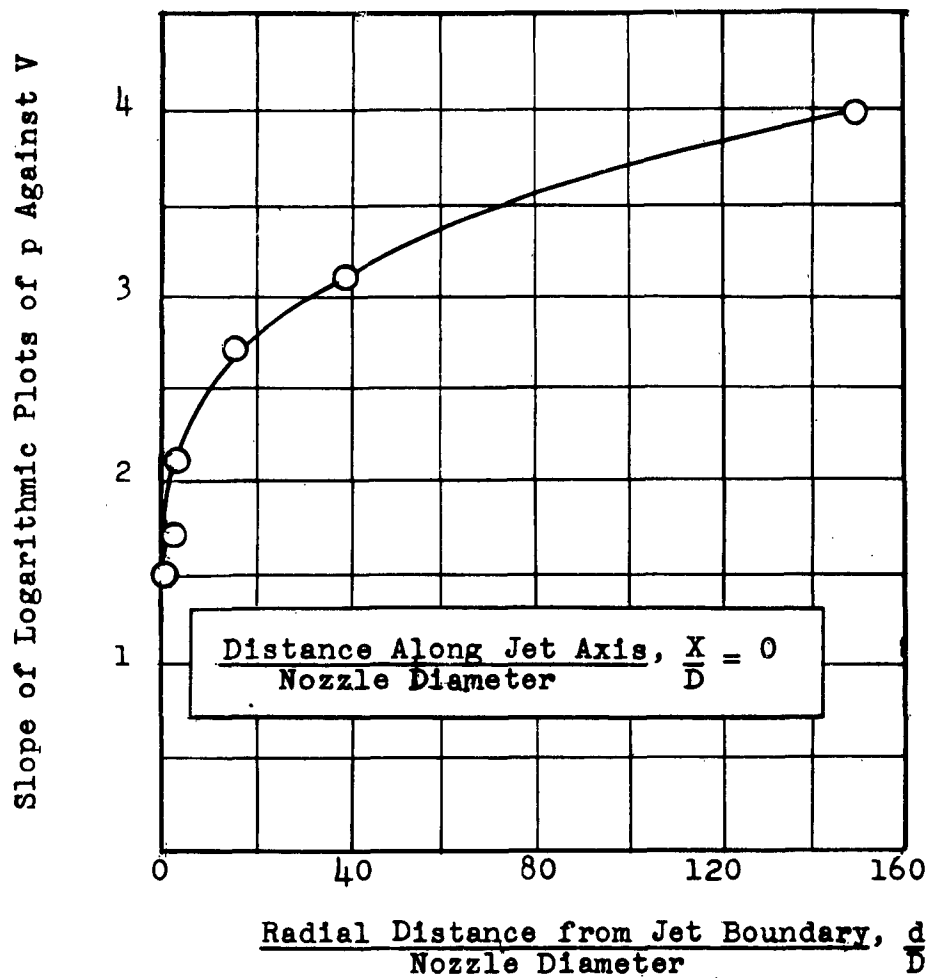
Figure 23



Engine Afterburner Noise Level (Distance from Jet Exit=200')

Figure 24

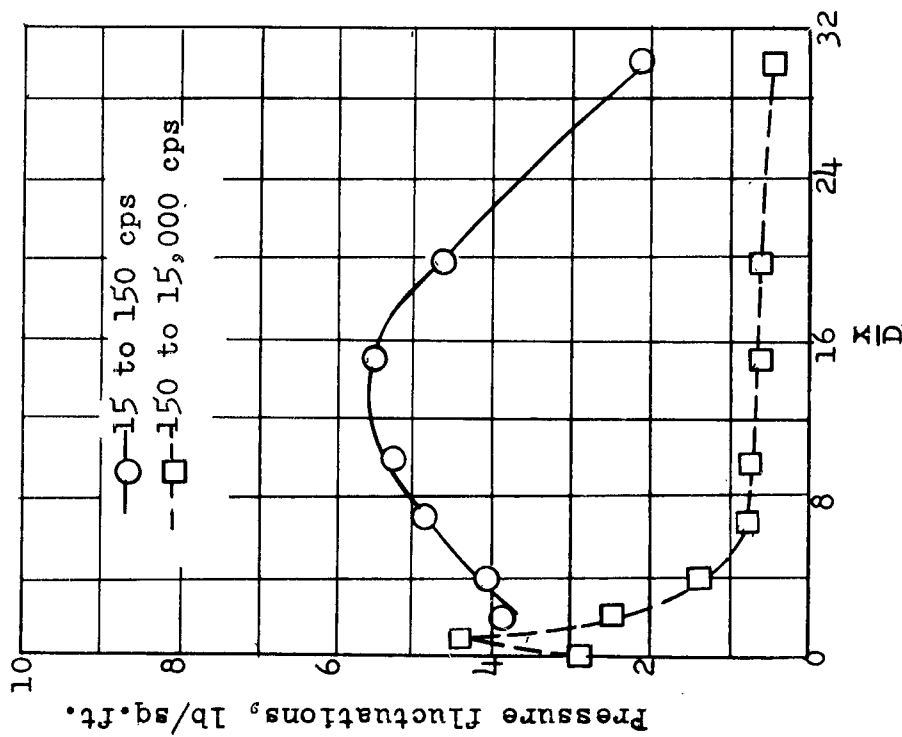
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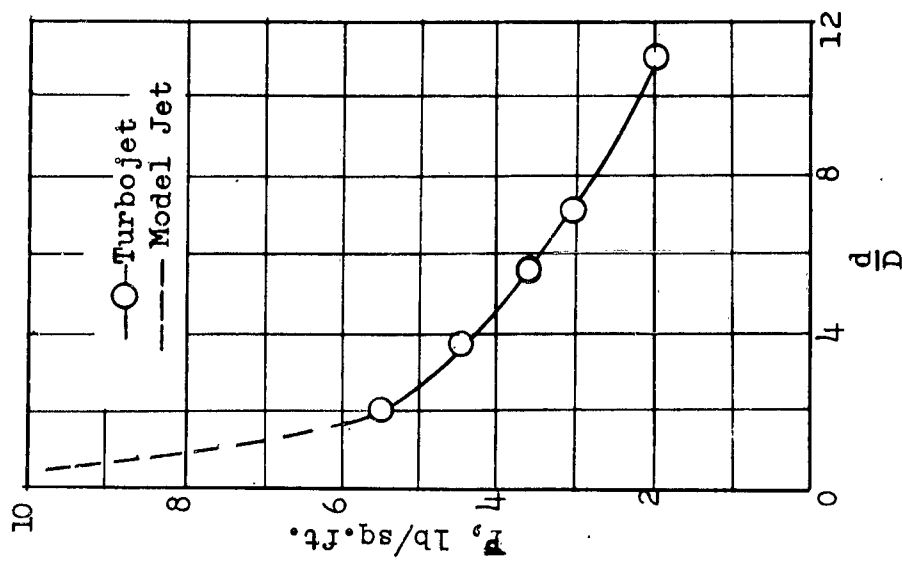
Effect of Radial Distance on Slope of
Over-All-Sound Pressure Curves

Figure 25

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(a) Effect of axial distance
 $\frac{d}{D} = 2.0$

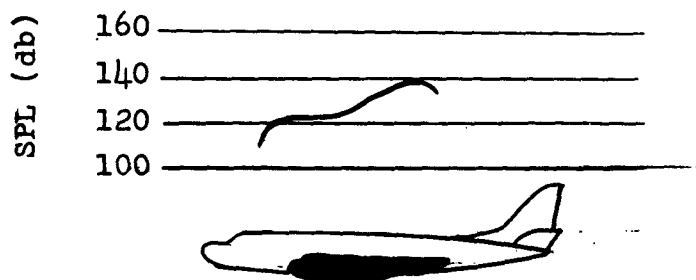


(b) Effect of radial distance
 $\frac{x}{D} = 15$

X-distance along flow axis
P-overall pressure fluctuations lbs/sq. ft.
d-radial distance from 150 boundary
D-nozzle or orifice diameter

Figure 26-Effects of Distance on Magnitude of Pressure Fluctuations
of Full Scale Jet Operating at Rated Thrust.

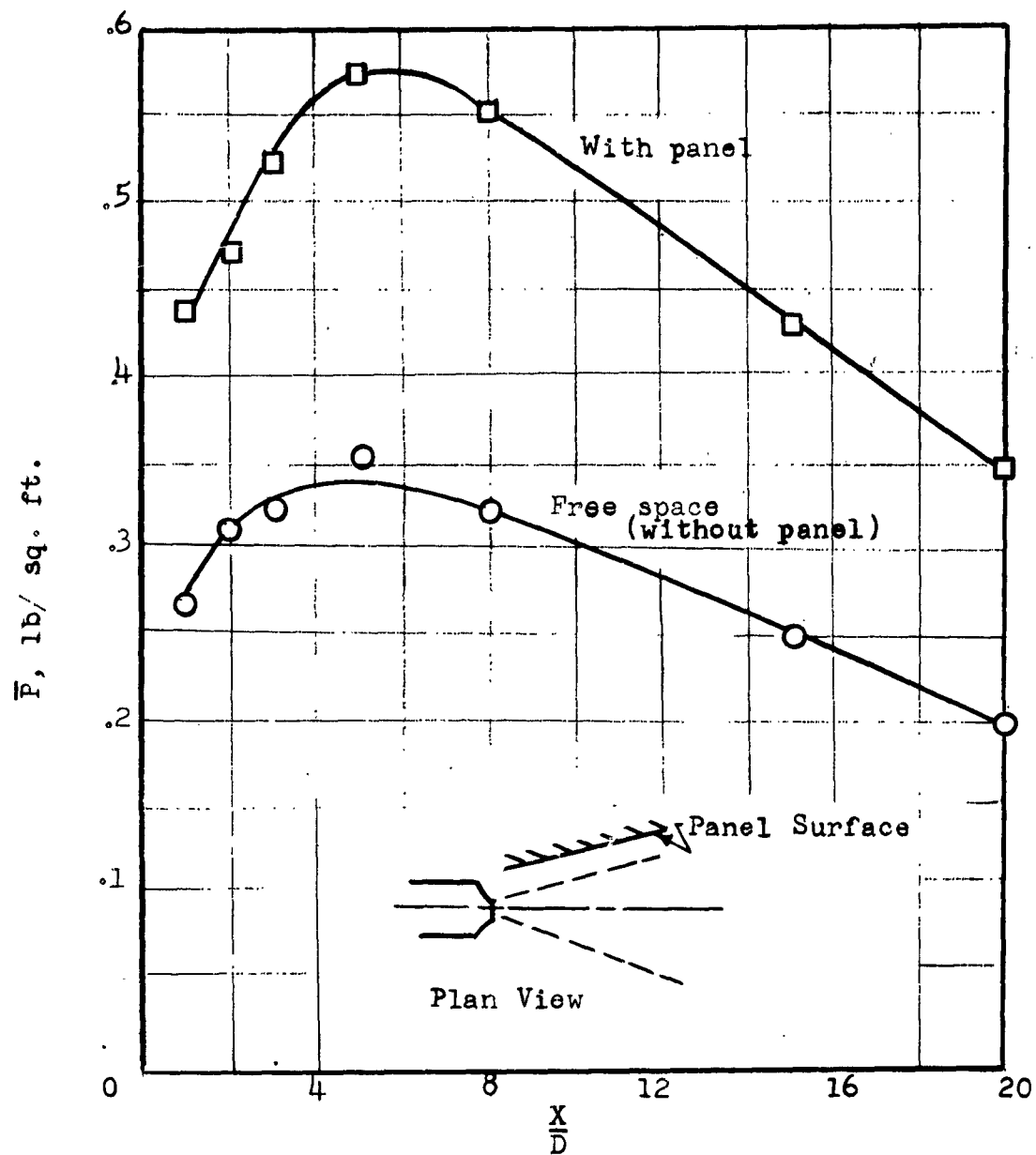
panels, depending upon the engine's location. An investigation has been conducted by N.A.C.A. to study the effect of panel location on panel surface pressures and sound distribution in the near field (24). Results of these investigations for panels placed parallel to the jet axis and parallel to the jet boundary, are shown in Figures 28 and 29. Note that the pressure fluctuations on panels placed parallel to the jet boundary increase by as much as 50 to 80 percent over values obtained in a far field. This pressure doubling effect has been observed on full-scale jet transports. (See Figure 27) A study has been performed (25) which states that it is possible to predict the stresses in aircraft skin panels caused by the excitation of jet noise by a generalized harmonic analysis.



Jet Thrust/Engine = 2770 lb (Static)
 Jet Exit Diameter = 1.27 ft.
 Altitude = Sea Level
 Jet Velocity = 1600 ft/sec.

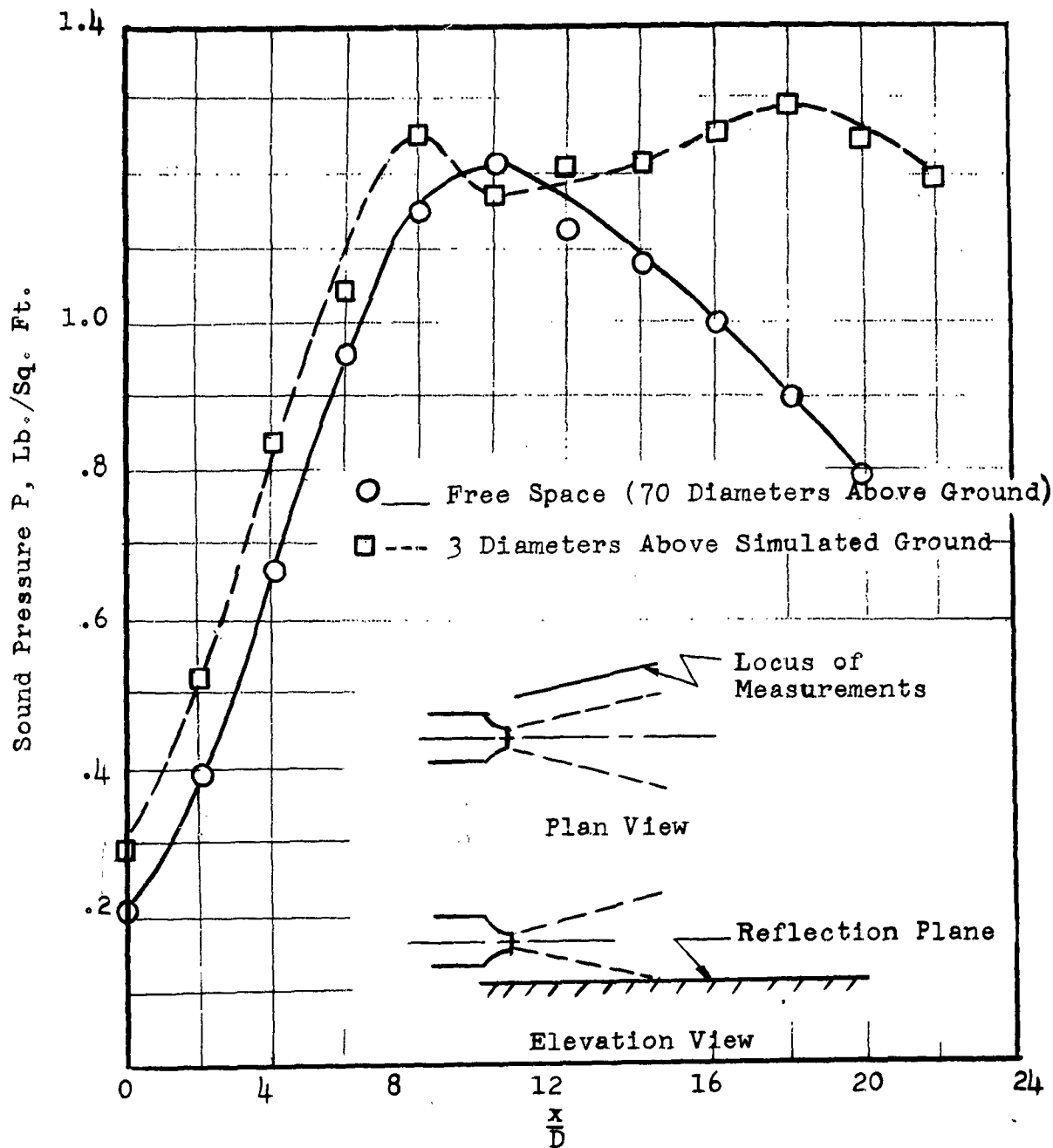
Distribution of SPL Along Fuselage of Transport
 Using Four Jet Engines

Figure 27



Effect of Panel on Pressure Fluctuations in 1-inch Jet
 $(\frac{d}{D} = 1.5; V = 700 \text{ fps.})$

Figure 28



Ground Effect on Pressure Fluctuations

$V = 1,715$ fps

$\frac{d}{D} = 2$

Temperature = 1750°R

Figure 29

Prediction of Acoustical Power - Subsonic Exhaust Jets

Researchers have been able to correlate with some success, model jet and full-scale jet engine noise characteristics. As a result, model jet studies have become valuable tools in determining jet noise characteristics. In conjunction with the experimental studies, several investigators have developed expressions to predict acoustic power of subsonic jets. Tyler and Perry (26) have suggested that the exponent for jet velocity be six as opposed to the eighth power which appears in Lighthill's relation, $V^8 d^2$. Specific thrust (jet thrust/weight flow) is suggested as a means of determining the acoustic power of a turbojet engine. For subsonic conditions, specific thrust is essentially the effective jet velocity; its magnitude can be obtained directly from full-scale engine tests.

$$\text{Acoustic Power} \propto (\text{Specific Thrust})^6 (\text{Area})$$

Noise data obtained from numerous engine tests indicate that the relation can be expressed as:

$$\text{PWL} = 60 \log_{10} (\text{Specific Thrust}) + 10 \log_{10} (\text{Nozzle Area}) + 43 \quad (\text{XI})$$

where reference power = 0.9×10^{-13} watts
specific thrust = lb-sec/lb
nozzle area = in²

Mercer and Dyer (27) have related acoustic power to fluid characteristics of the jet by dimensional analysis. The empirical relation for acoustic power is then:

$$\text{Acoustic Power} \propto (\text{Jet Power})(K^2)$$

$$\text{where } K = \frac{(\text{jet power})}{(\text{static temperature})^{1.8} (\text{diameter})} \quad (\text{XII})$$

From numerous full-scale engine tests, a proportionality constant has been established so that the above relation can be expressed as:

$$\text{Acoustic Power} = (4.2)(10^{-3})(\text{Jet Power})(K^2) \quad (\text{XIII})$$

where jet power = $\frac{1}{2} \rho A V^2$, expressed in watts
static temperature - °R
jet diameter - inches
acoustic power - watts

Based on these relationships, Mercer and Dyer developed a monogram (Figure 30) which can be used to estimate the acoustic power of a turbojet engine. Comparison of this method with the $V^8 d^2$ and specific thrust relations by Mercer and Dyer (27) indicates that the K^2 relation shows slightly better correlation (Figures 31 and 32) with noise data. However, a spread of about 3 db is still present. Comparison of $V^8 d^2$ and K^2

relations indicates that these expressions differ by a factor of $(\text{velocity})(\text{diameter})^2/(\text{static temperature})^{6.6}$. When typical values of non-afterburning engines are substituted in this expression, it is found that this factor has a value which is equivalent to slightly less than one decibel. Thus, it contributes very little towards determinations of the total acoustic power of turbojet engines. There is some skepticism among investigators concerning the K^2 relation and this feeling is due strongly to the lack of a technical basis for the introduction of thermal conductivity in Mercer and Dyer's analysis. Applicability of this relation in predicting acoustic power of afterburning engines may be questionable; further investigation is in order.

Test data on higher thrust engines are being gathered so that a better evaluation of analytical methods for predicting sound power of jet engines operating at afterburning and non-afterburning conditions can be made.

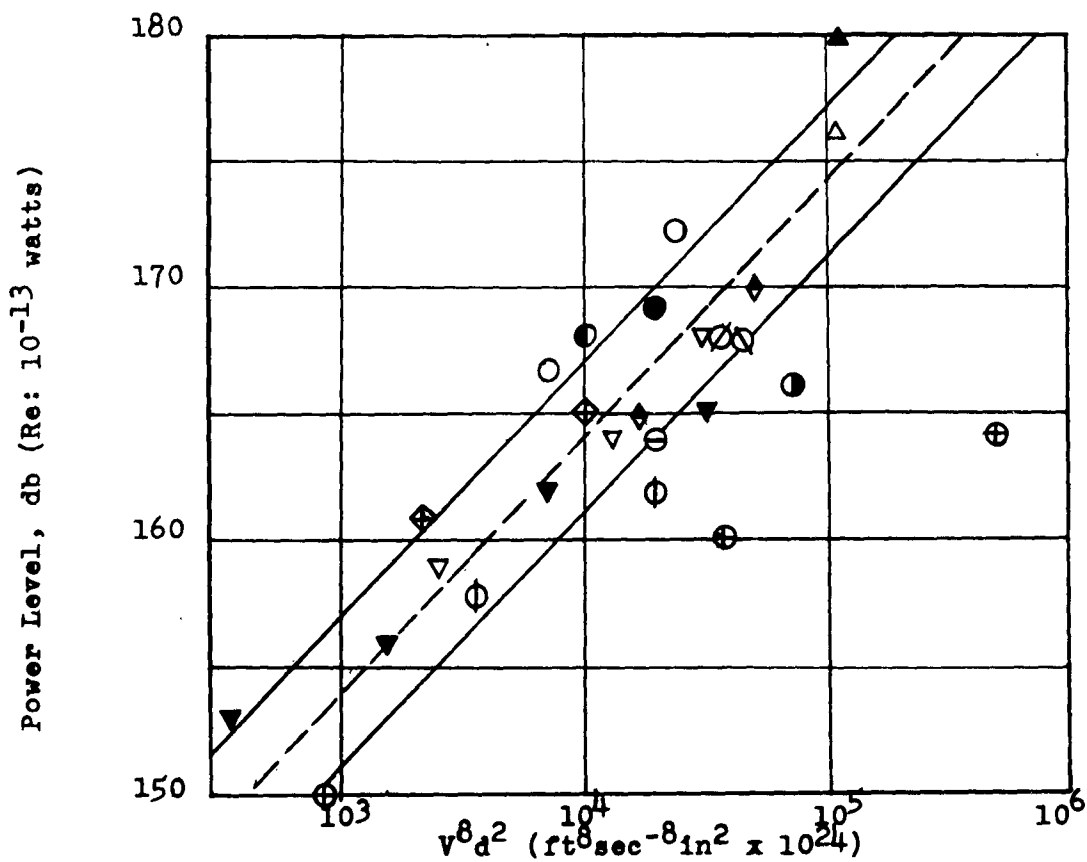
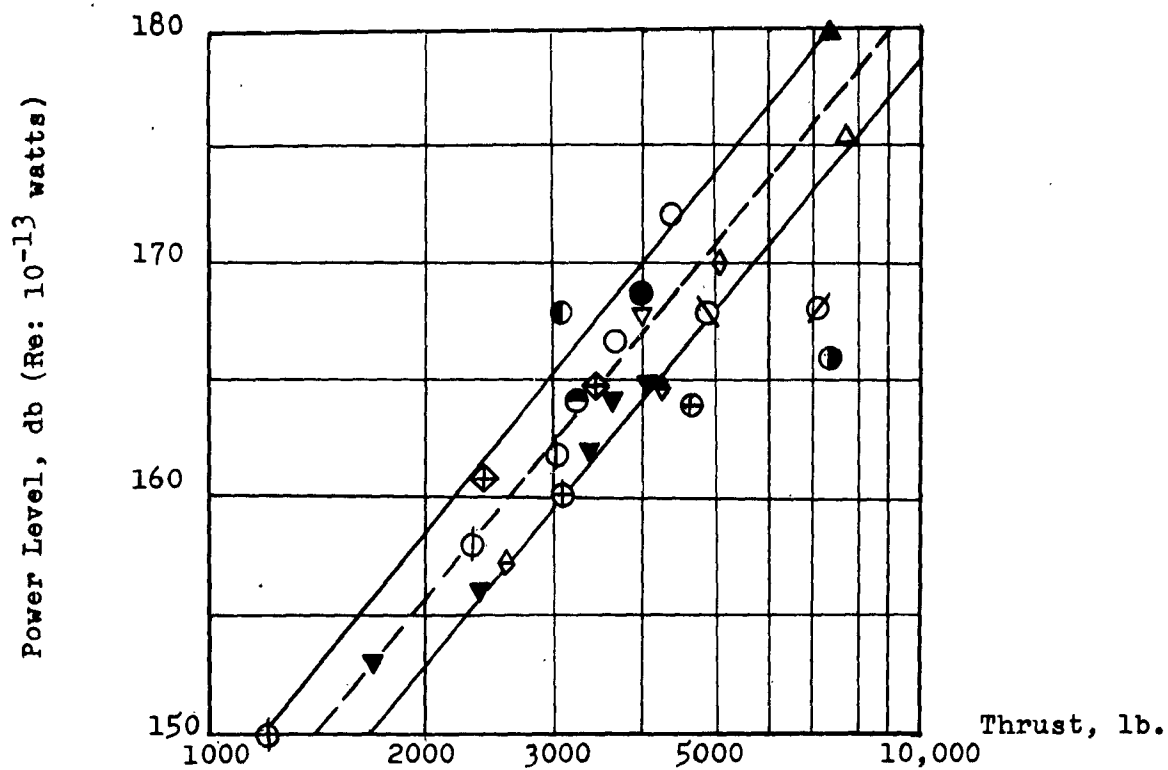
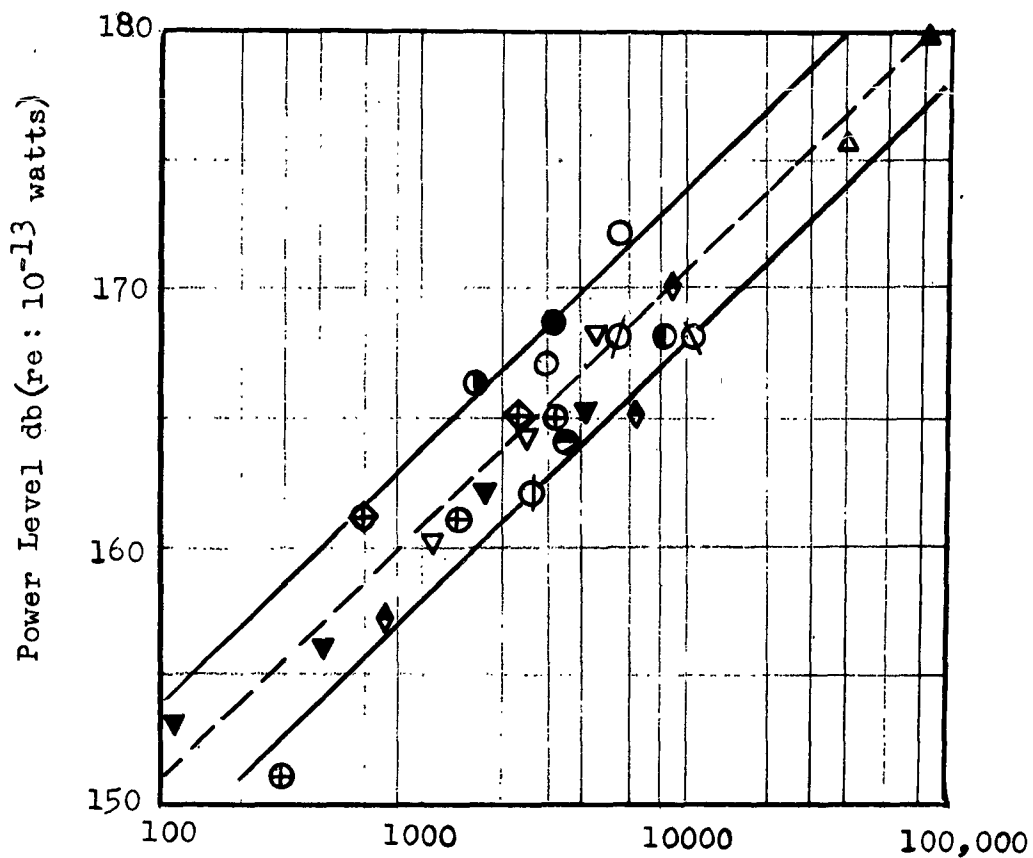


Figure 31. - Comparison of Engine Noise Data
WADC TR 55-383, Part I



(4.2) $10^{-3} WK^2, \text{Watts}^3 / R^{3.6} \text{ in}^2$
 K^2 Method of Engine Noise Data Presentation

Figure 32

WADC TR 55-383, Part I

3. Exhaust Jet Noise - Supercritical Flow

To date, most theoretical and experimental efforts with respect to jet noise have been concerned with subsonic or unchoked jet flow. The noise problem of jet nozzles operating at supercritical flow conditions has received relatively little attention, possibly because turbine engine exhaust nozzles were operating unchoked for maximum power, static sea level conditions. But as the speed and altitude demands of jet-powered aircraft have increased, it has become necessary to raise the power level of turbojet engines. As a result, some current and practically all proposed turbine powerplants at maximum power, static and take-off conditions will be operating with supercritical pressure ratios across the exhaust nozzle. The very little information on jet noise that does exist for choked flow serves to indicate that the mechanisms of noise generation for this operating condition are not wholly understood.

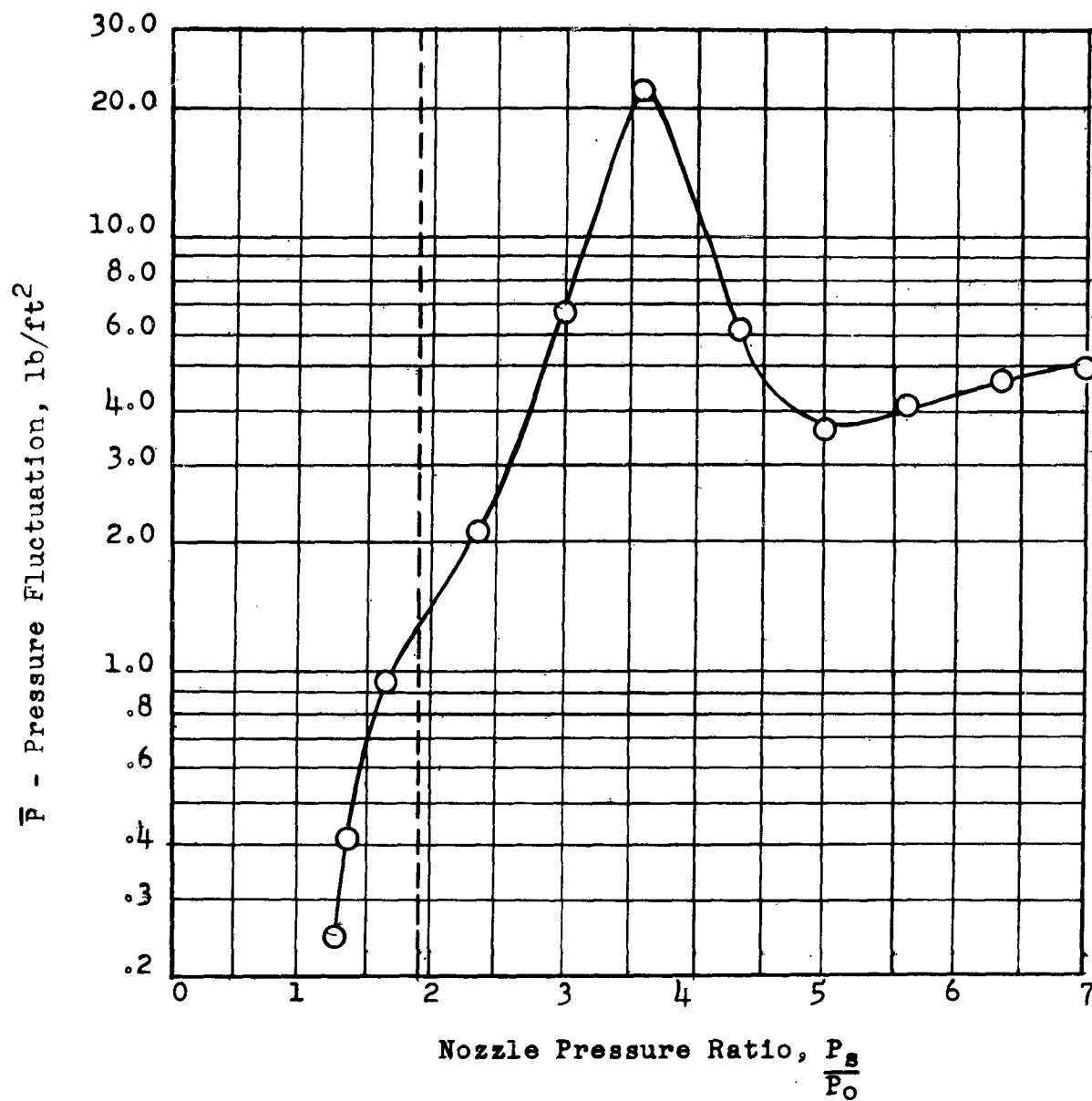
The bulk of the available experimental data has been obtained with cold flow model jets; the tests indicate that convergent nozzles operating at pressure ratios above the choking condition exhibit a sudden change in frequency spectrum, at particular pressure ratios, which has a characteristic intense, discrete frequency component. This condition is known as "screech." The magnitude of this phenomenon reaches a maximum at a particular pressure ratio after which it decreases with increasing pressure ratio. For example, with a 1" diameter jet, screech reached a maximum intensity at a pressure ratio of 3.67 and disappeared at a pressure ratio of 5. (Figure 33) Schlieren observation of model jets show that flow disturbances caused by partly formed toroidal vortices and oscillating shock waves produce screech. Data indicate that the frequency of screech is related to shock spacing and is inversely proportional to the nozzle diameter for a given pressure ratio, (24). Figure 34 shows the screech frequency at various total pressure ratios for both orifice and nozzle jets.

During screech, axial pressure fluctuations occur along the jet. Figure 35 shows such a pressure survey for a sharp-edge orifice taken approximately 0.1 diameters from the jet boundary. A British investigator (22) states that screech frequency for convergent nozzle jets (cold flow jets) can be expressed approximately by:

$$f = \frac{1}{3} \left(\frac{c}{D} \right) (R - R_c)^{-1/2} \text{ (for two-dimensional jet)}$$

$$f = \frac{1}{5} \left(\frac{c}{D} \right) (R - R_c)^{-1/2} \text{ (for axially symmetric jet)}$$

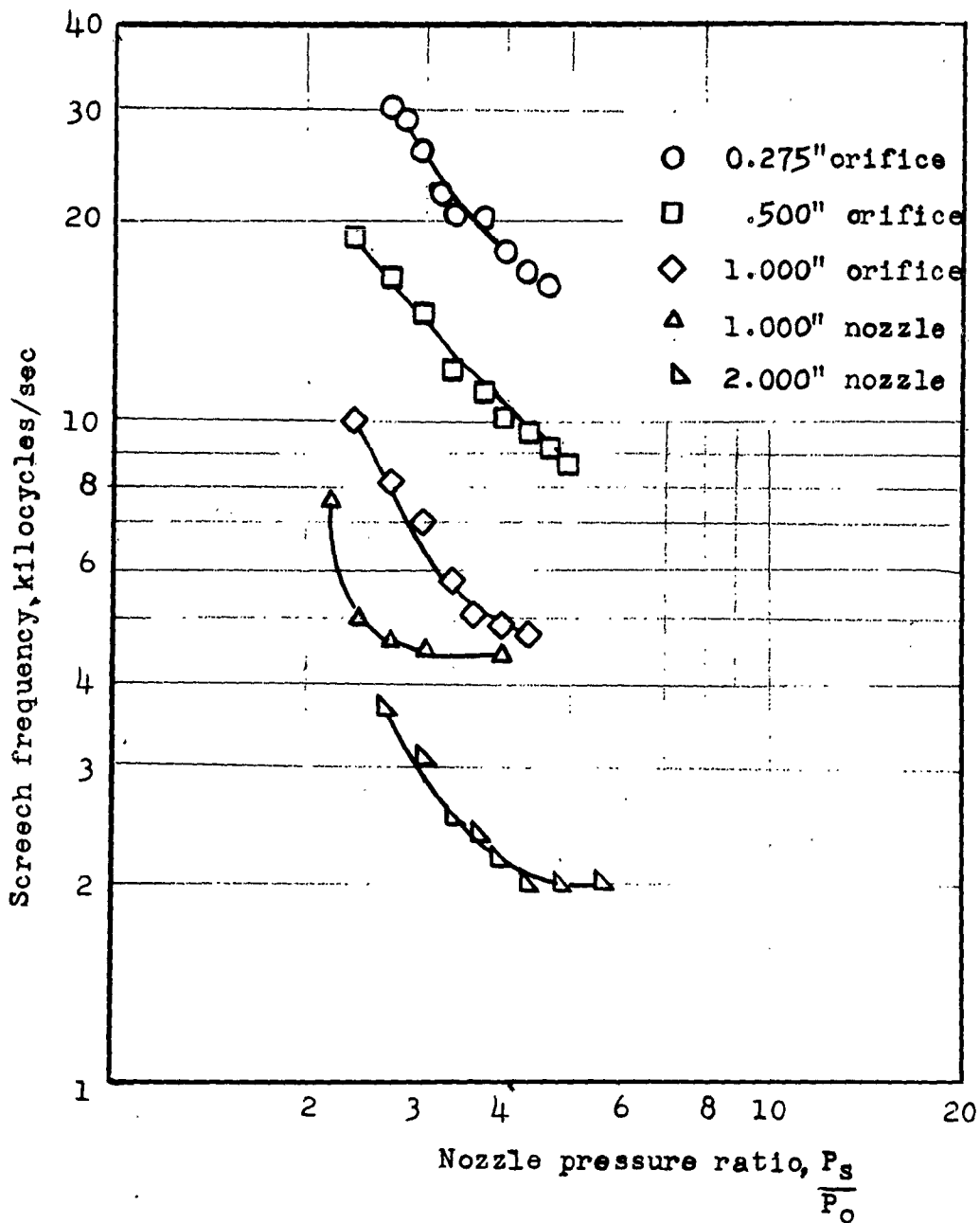
where f = screech frequency, cps
 c = sonic velocity



Effect of Nozzle Pressure Ratio on Magnitude of Pressure Fluctuations ($D=1$ inch; $\frac{X}{D} = 2.5$; $\frac{d}{D} = 0.5$)

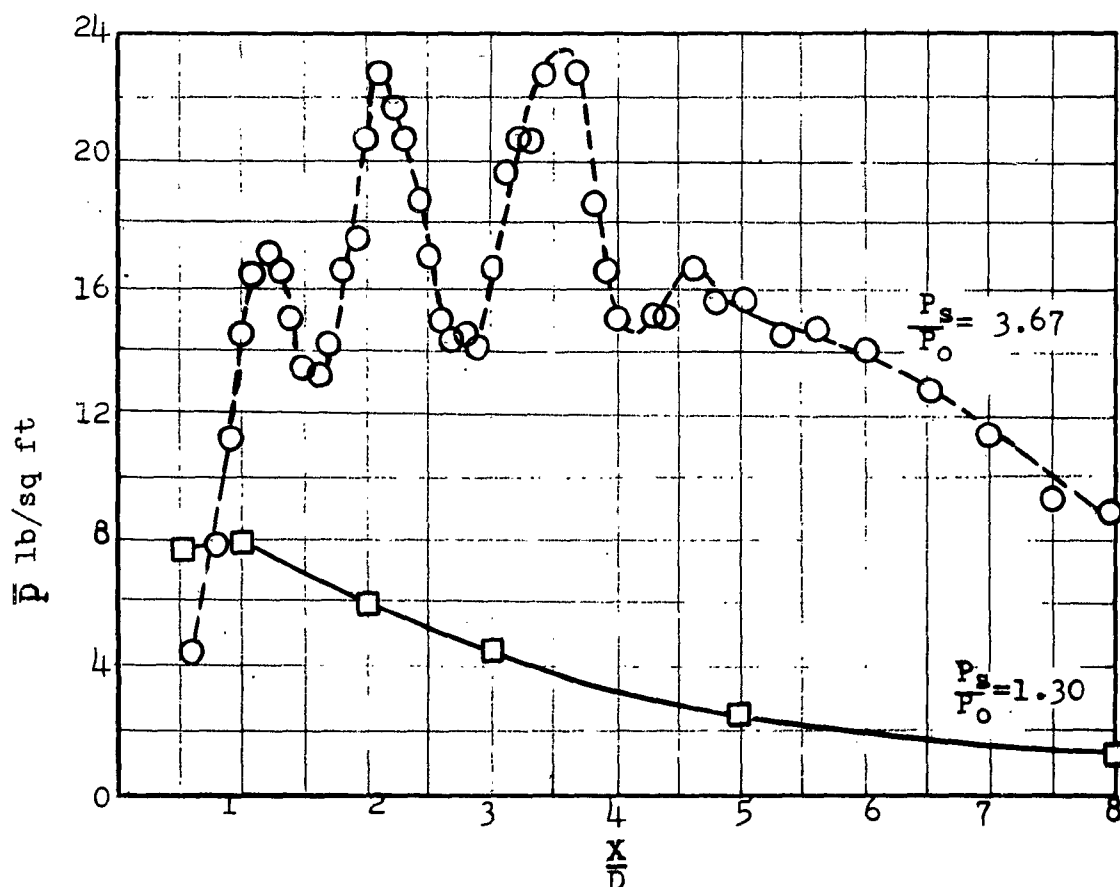
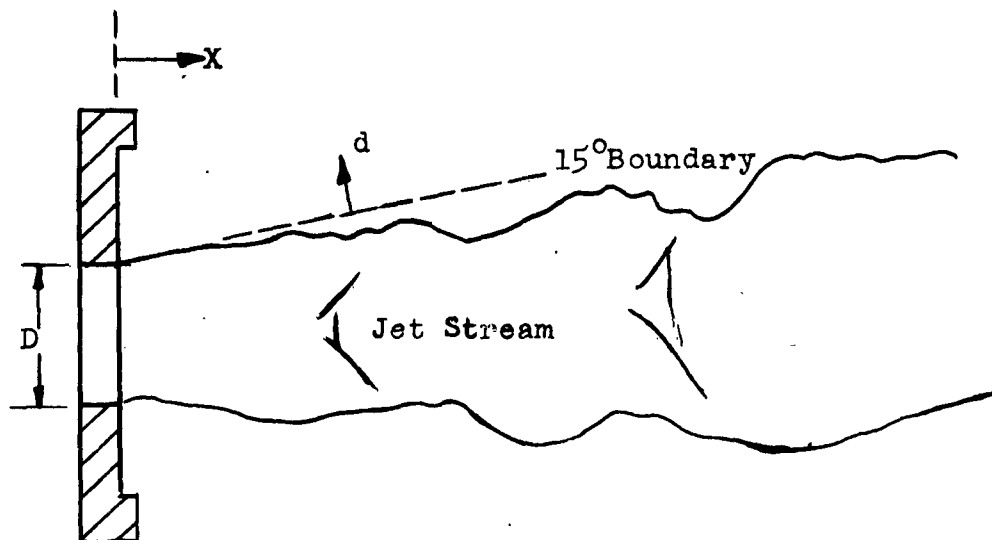
Figure 33

WADC TR 55-383, Part I



Effect of Jet Diameter on Screech Frequency

Figure 34



AXIAL DISTRIBUTIONS OF MAGNITUDE OF PRESSURE
FLUCTUATIONS FOR SHARP-EDGE ORIFICE
($D = 1$ inch: $\frac{d}{D} \approx 0.1$)

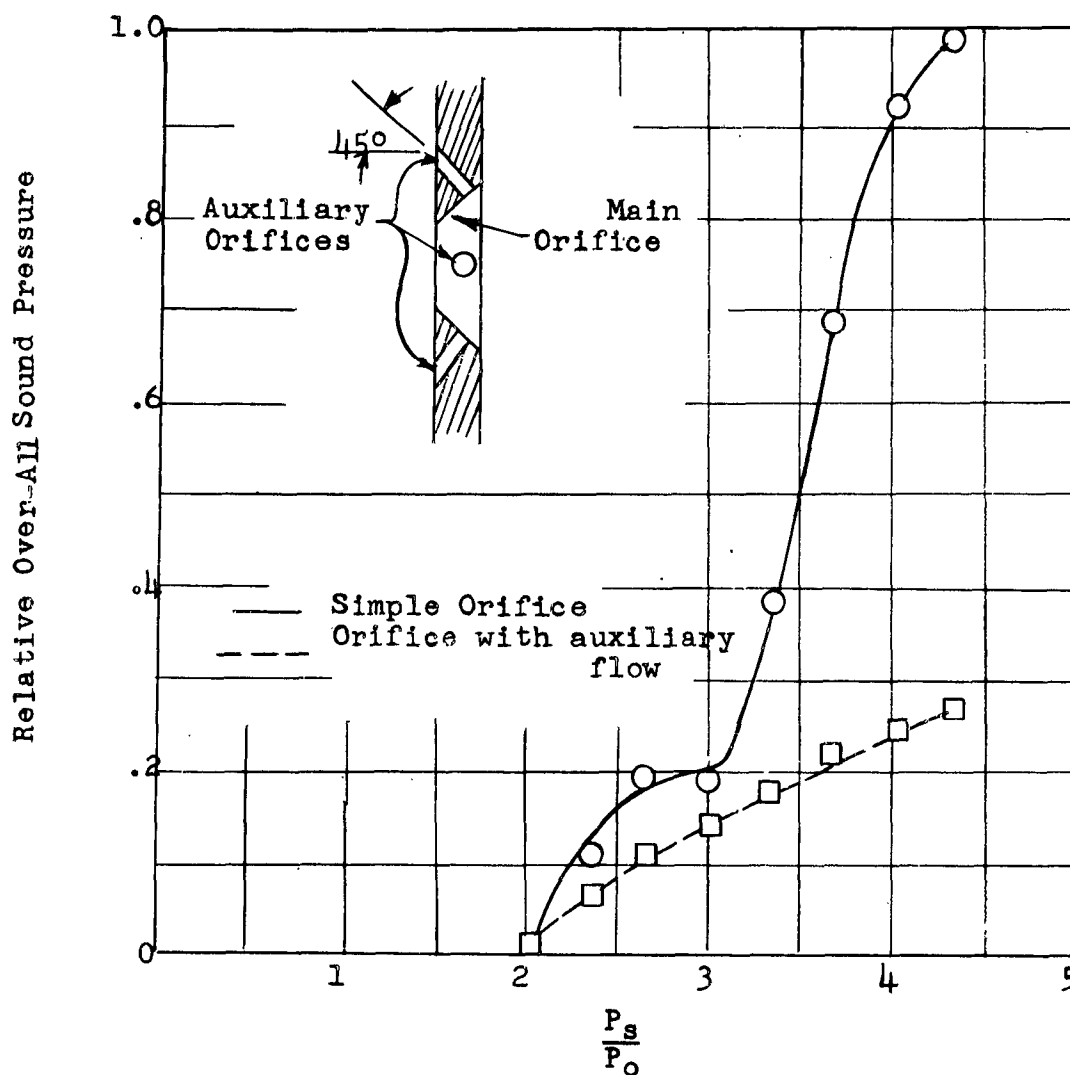
Figure 35

D = jet width or diameter
R = nozzle pressure ratio
 R_c = critical pressure ratio

Thus, noise from a choked convergent jet is believed to be generated by the turbulent mixing of the jet with the atmosphere as well as by the formation of torroidal vortices and oscillating shock waves. Elimination of the torroidal vortices has been found to reduce substantially the acoustical energy generated. One method or device which has been tried successfully on scale model jets (24) involves injection of an air stream by a series of auxiliary orifices into the main jet stream. Figure 36 indicates the noise reduction obtained by this method. A British investigator (28) has found that very small notches on the edge of choked model jets (convergent type) produce a noticeable reduction in noise level. (See Figure 37.) This investigator also conducted model tests in which a wire screen placed at the nozzle exit gave evidences of some noise reduction.

Test data (Figure 38) on a convergent-divergent nozzle designed for $M = 1.36$, i.e., for a pressure ratio of 3.1, indicated that the acoustic power radiated from the jet at the design pressure ratio obeyed Lighthill's eight power velocity law and deviated from it between pressure ratios of two to three. This indicates that Lighthill's theory for turbulent mixing noise generation may hold for both subsonic and supersonic velocities as long as the flow is shock free. Therefore, for high nozzle pressure ratios, a properly designed convergent-divergent nozzle provides not only greater thrust, but can be quieter than a sonic (convergent) nozzle operating at the same pressure ratio.

Analysis of rocket jet noise shows that the noise field is directional and that the angular distribution of sound energy bears a marked similarity to subsonic jet noise generation. The maximum sound pressure appears to occur at about the same angles of 30° to 45° from the jet axis. The noise has a random amplitude with most of the sound energy located in the low frequency range of 20 cps to 1500 cps. The frequency spectrum has a curve similar to a subsonic jet peaking over a wide range. This peak is found to vary with azimuth angle in a manner similar to that for subsonic noise, i.e., the high frequency bands are concentrated at higher angles to the jet axis than the lower frequency bands. (See Figure 39.)



Effect of Auxiliary Orifices on Relative Over-All Pressure Fluctuation Magnitude

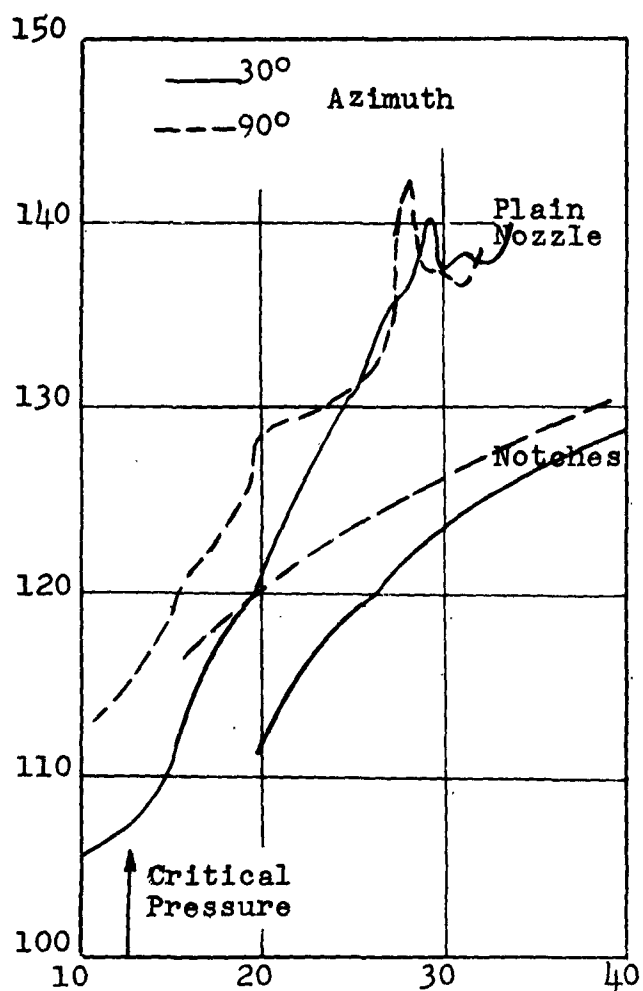
(Auxiliary orifice dia. = 0.031"

Main orifice dia. = 1.0" = D

$\frac{X}{D} = 3$)

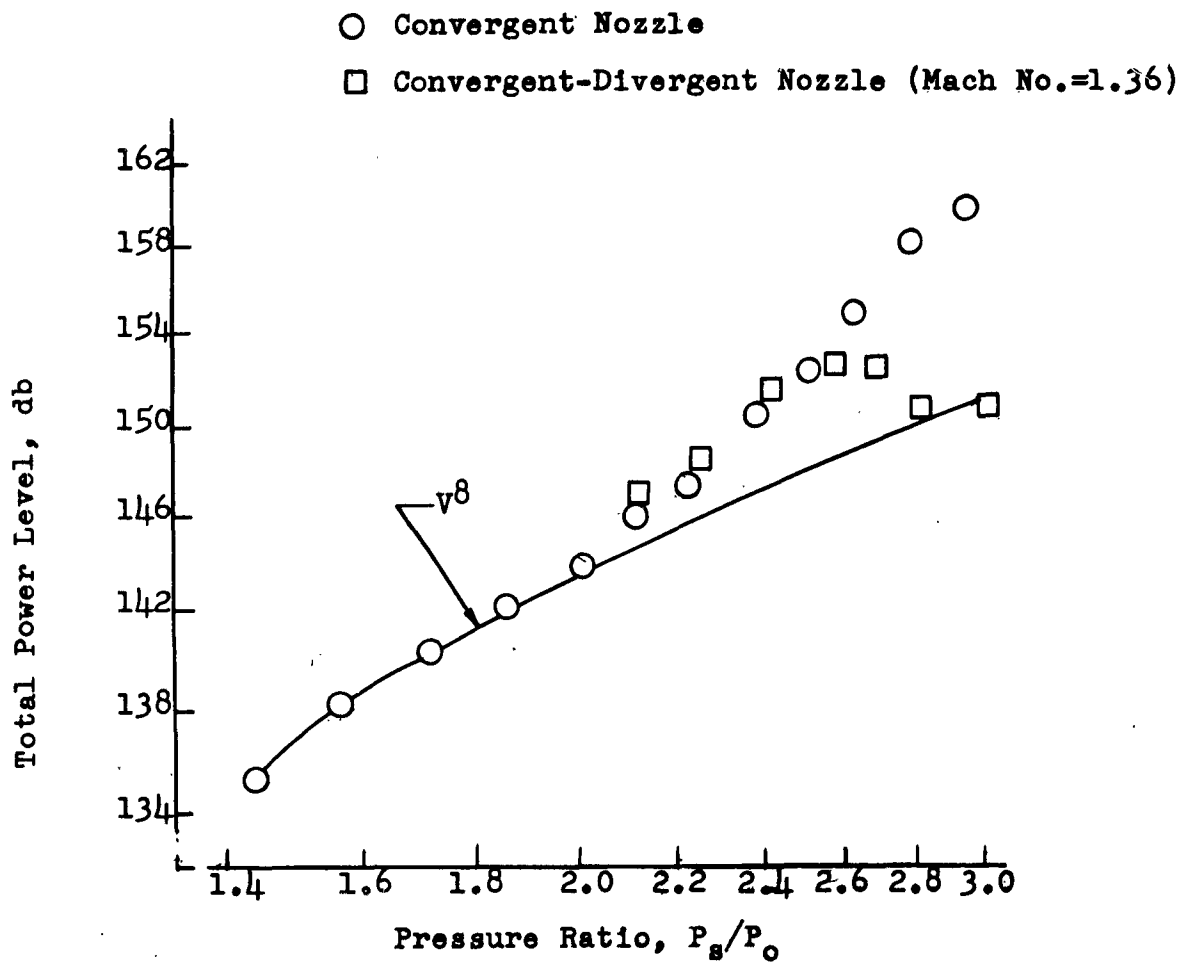
Figure 36

Total Noise Level (Re: 0.0002 Dynes/cm²)



Jet Pressure, psi
Effect of Notches on
Noise Level of a Choked Convergent
Nozzle

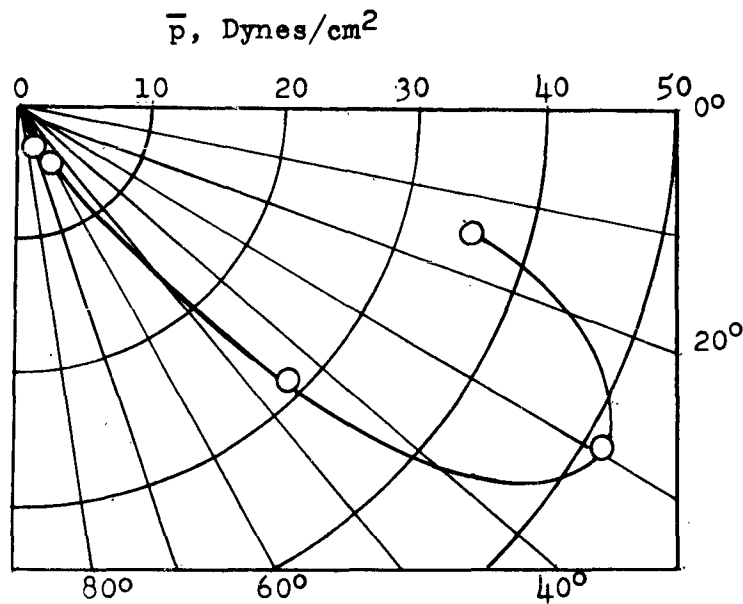
Figure 37



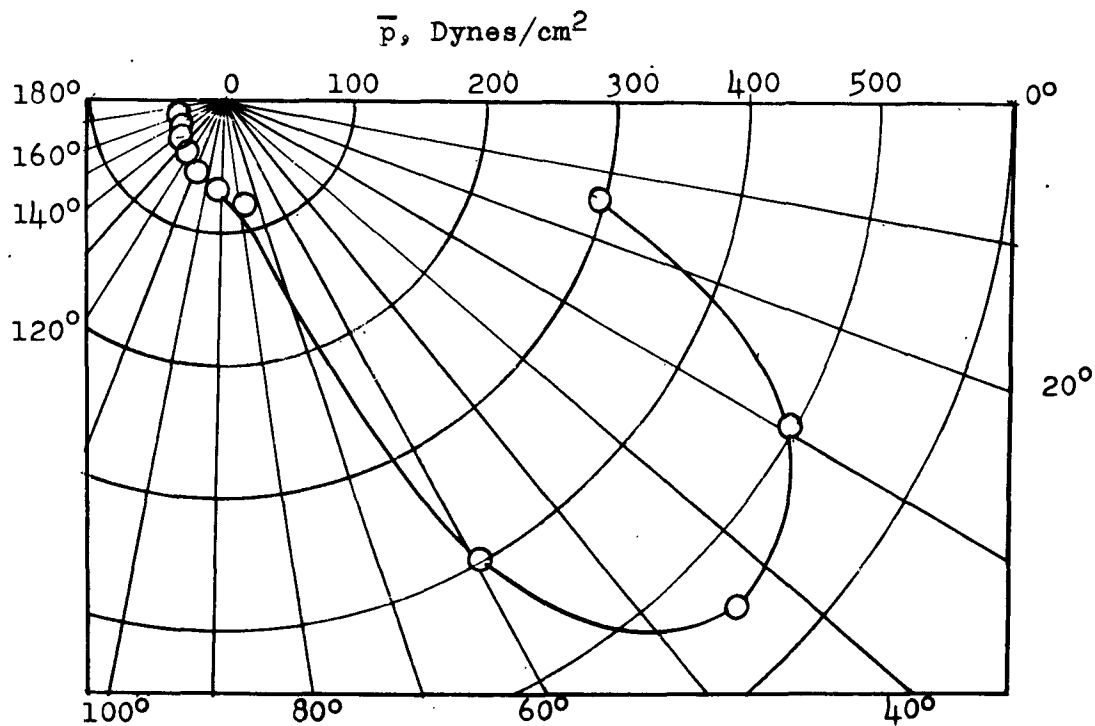
Effect of Pressure Ratio on Total Power Level

Figure 38

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(a) 0 to 40 cps,



(b) 20 to 20,000 cps.

Angular Distribution of Sound Pressure From a
Rocket Engine
 $x = 50$ ft.
Thrust = 1,000 lb.
 $V = 5,340$ ft/sec

Figure 39

4. Jet Noise Suppression Devices

From the standpoint of personnel safety and comfort, noise developed by the exhaust jet of contemporary turbine engines has been found to be intolerable. As a result, numerous methods of suppressing jet noise have been studied both in this country and abroad. The following discussion reviews these efforts directed towards noise control.

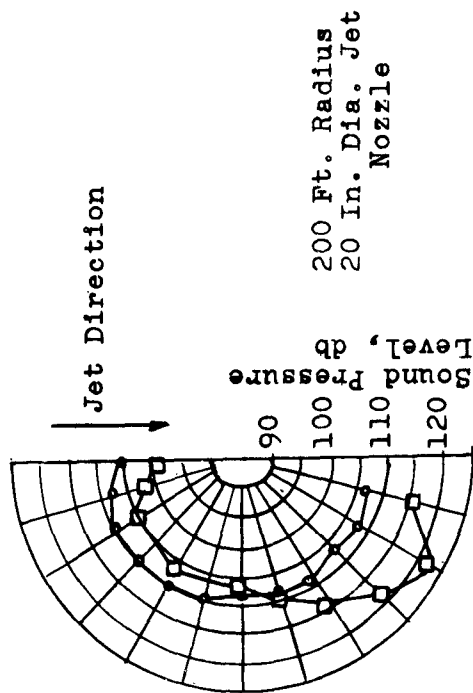
The understanding of aerodynamic jet noise phenomena has permitted investigators to consider devices which reduce noise levels at the source and are a part of the engine installation. Current turbojet engine noise levels must be reduced on the order of 30 decibels (SPL) in order to provide suitable working conditions for personnel. Besides providing the necessary noise reduction, these devices should not affect basic engine performance.

From the nature of jet noise generation, the investigators concluded that the over-all noise level could probably be reduced by changing the turbulent mixing region through a reduction in jet velocity, and a change in jet velocity distribution and/or an increase in the spreading characteristics of the jet. Many devices for accomplishing this have been tested - most of them with little success.

a. NACA has conducted a program to investigate the effects of varying jet exit cross-sectional shapes on jet noise characteristics. Square, rectangular, elliptical, and truncated nozzles were tested; no appreciable reductions in noise were evident (29).

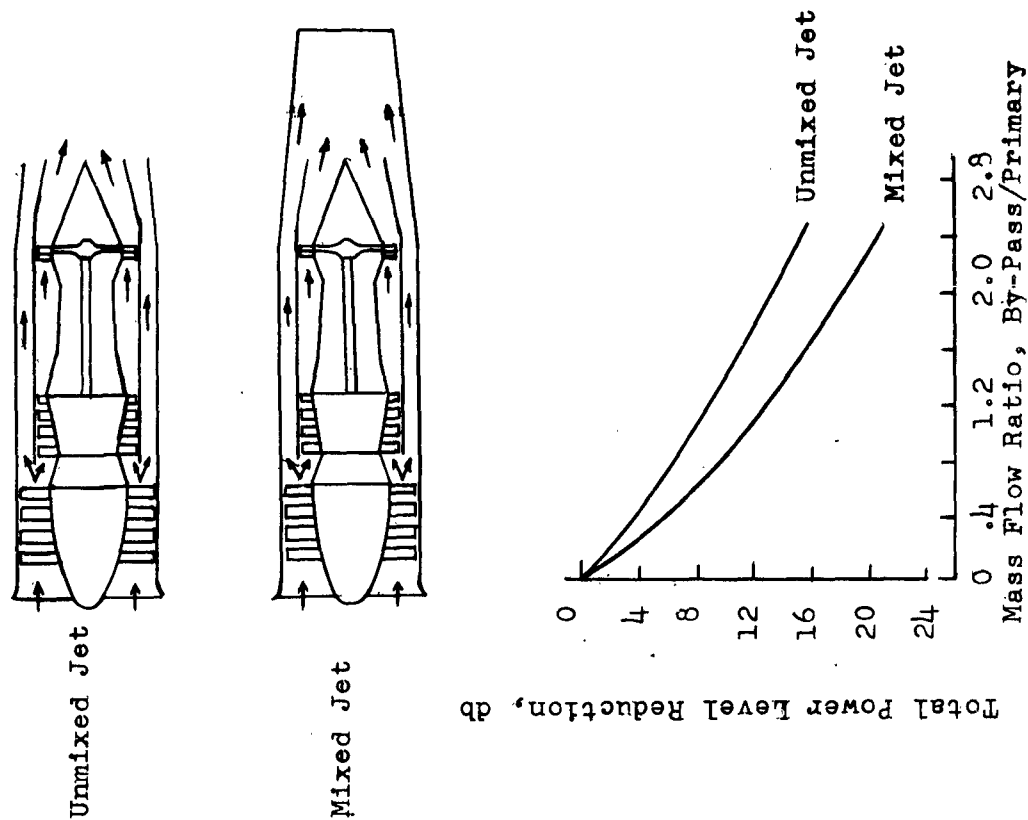
b. Two methods, water injection into the main jet stream as well as air injection, were investigated in reference 21 with the belief that absorption and shear gradient softening would result in some noise attenuation, but the results were unsatisfactory.

c. During experiments on model jets, it was found that as the nozzle diameter was reduced, the frequency spectrum shifted upward for a given jet velocity - thus placing the major portion of jet noise above the audible range (18, 30). Based upon these observations, Tyler and Towles investigated several perforated nozzle model configurations. One of these configurations was later tried on a full-scale engine and consisted essentially of a perforated tube closed at one end by a perforated cone. The total effective area of these perforations was made equivalent to the effective nozzle throat area of the basic engine. Results of their full-scale tests indicated a substantial reduction in the audible portion of the noise spectrum; engine performance, however, was adversely affected. Such a device in its present stage of development could find use in ground run-up operation.



Effect of Screen on Engine Noise Field

Figure 40



Comparison of Noise Reduction of By-Pass and Turbojet Engines at Equivalent Thrust Rating

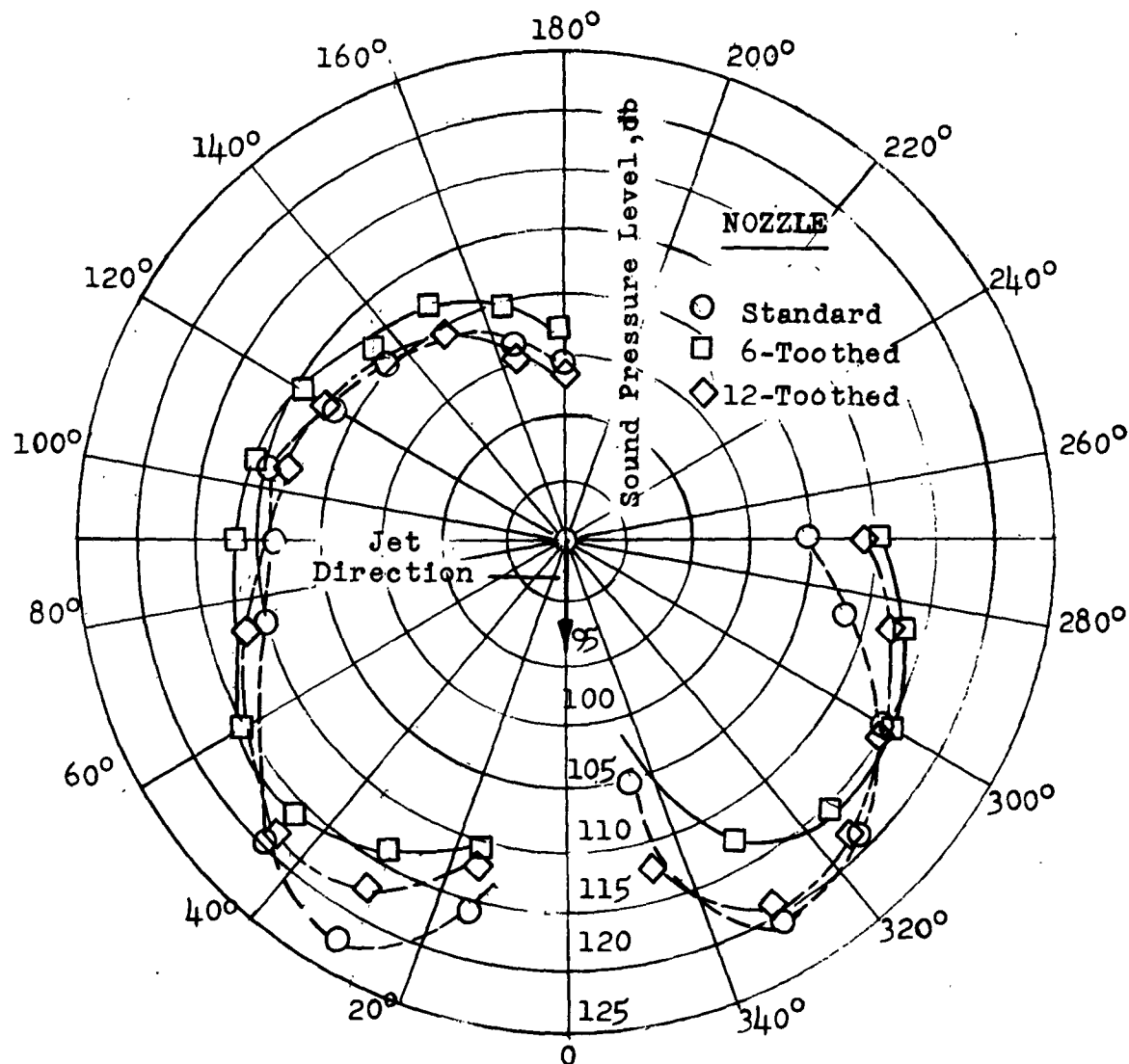
Figure 41

d. Lassiter and Hubbard (24) found that a wire screen placed downstream of an unchoked model jet gave significant reductions in jet noise levels. A full-scale turbojet engine was then tested with a wire screen located at various positions downstream of the jet exit. The results indicated that reductions in the acoustical sound power level of as much as 7.5 db were possible and were probably the result of reduced jet velocity downstream of the screen. However, these reductions were also accompanied by a thrust loss of as much as 60 percent (31). Downstream of the screen, the sound pressure level was reduced about 12 db, while upstream of the screen the SPL was increased about 7 db. The net result was that the sound field was no longer directional (see Figure 40). It was also found that the position of the screen was not only critical in producing noise reduction but influenced structural damage of the screen due to formation of resonant frequencies. For screens of 1" to 4" mesh, the best location was found to be close to the tailpipe, approximately 6 to 15 inches downstream of it. It appears that this noise suppression scheme may find use in ground run-up operation of jet planes.

e. Ejector nozzles have also been investigated with the thought that the shear gradient across the jet would be softened by the mixing processes and thus would cause some noise reduction in comparison with the basic jet nozzle. Several investigators claim that this device offers no reduction in jet noise levels, but no data has been published to date which show the results of these investigations.

f. A coaxial jet, i.e., a hot jet surrounded by a cooler stream, has been studied by several workers in the field of jet noise; conflicting data appears to exist based upon the results of their work. In reference 21, it is stated that the test results indicated that the cold outer airstream does not show an appreciable effect on the noise level of the hot jet and that the position of the inner nozzle exit, whether it is in the plane of or upstream of the outer nozzle exit, has no effect on the noise level of the hot jet. However, British data (6) indicates that if mixing is almost complete, a reduction in noise results. It is stated in this reference that calculations and actual test data on a by-pass engine showed an appreciable reduction in sound power compared to a turbojet engine having approximately the same thrust rating. It was shown that this is due principally to the lower effective jet velocity which results from the two streams mixing in the by-pass engine. The by-pass engine tested was a Conway engine which has low pressure air by-passing the combustion chamber and turbine and mixing with the hot combustion gases in the jet pipe. Test data taken at 50-foot radius indicated a noise reduction of about 8 to 10 db (SPL) over that of a turbojet of equivalent thrust rating (6). Predicted values of probable noise reductions obtainable with by-pass engines in comparison with turbojet engines are illustrated by Figure 41 (29). Note that a turbojet of comparable thrust corresponds to a mass flow ratio of zero.

g. Another device, which has been studied by NACA and British investigators, was a tooth-type nozzle. "Teeth" or bars inserted in the jet exhaust at several angles caused the jet to spread quickly at a large angle to jet axis. This method achieves a noise reduction by causing the jet to mix more quickly as well as by reducing rate of shear. A full-scale turbojet engine fitted with "teeth" was first tested by the British and the results indicated that this device



Polar Diagram of Sound Field
Distance from Nozzle = 200 Feet

Figure 42

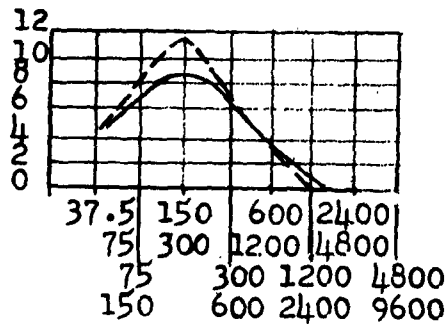
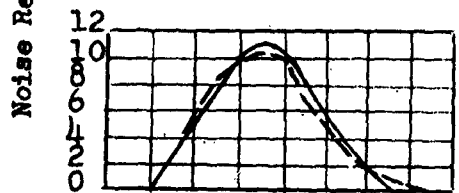
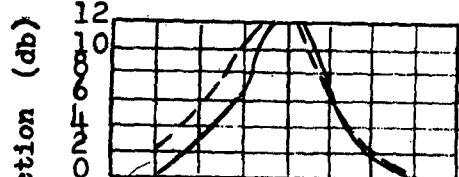
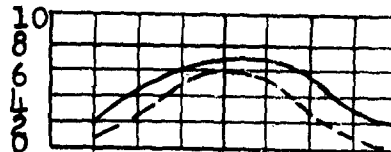
provided a reduction in sound pressure level (9). However, further investigation by NACA (8) revealed that this reduction only resulted near the 30° azimuth and that the sound pressure levels at the azimuths greater than 60° were increased (see Figure 42). This rearrangement of the sound pressure in the field was found to give the same total radiated acoustic power as the original configuration. In addition to providing little noise reduction, a thrust loss was also evidenced.

h. Results of tests run on the toothed nozzle indicated that rapid mixing as near the jet exit as possible could provide a reduction in noise generation without affecting the engine performance. This led to the investigation and later the development of the corrugated type nozzle by Rolls Royce, Ltd. for noise reduction (6). It was found in model and full-scale tests that this device produced a noticeable noise reduction over that of an equivalent conical jet nozzle of approximately 4 db (PWL). This decrease is achieved by reduction of sound intensities in the frequency range of 150 to 2400 cps, the range in which jet engine noise is centered.

The series of corrugated nozzles investigated varied in depth and number of corrugations. Test results showed that reducing the number of corrugations reduced the frequency at which most of the extreme noise intensities prevailed. (See Figures 43 and 44.) It was found that six corrugations resulted in a substantial noise reduction in the frequency range between 150 to 2400 cps. It was also found that increasing the half cone angle (angle of convergence of the inner wall of the nozzle) beyond 12° resulted in a noise reduction; but as the angle was increased beyond 12° , thrust losses were incurred.

Figure 45 shows the noise contours obtained from full-scale engine tests using a corrugated nozzle. It can be noted that the corrugated nozzle produces attenuation in the higher frequencies and that the sound pressure level contours for each octave frequency band are similar to those of the standard nozzle (Figure 20). The noise field from the corrugated nozzle contains no area which has more intense noise than the field for the standard nozzle, even though the spectrum from the corrugated nozzle consists of high frequency noise. It is seen also from the total noise contours that the maximum SPL occurs at an angle of 40° rather than 30° . This appears reasonable since it is observed that the noise spectrum consists primarily of high frequency sound. Sound pressure level reductions of about 8 to 10 db have been shown to be possible with this device. Such a reduction produces about fifty percent reduction in loudness. (Figures 3 and 4) The power levels of several conical nozzles are compared in Figure 46 with that of a corrugated nozzle installed on a full-scale turbojet engine to illustrate the resultant noise reduction.

Corrugations
No.
Depth



Noise Measured @ 50' Radius

_____ 15° from jet axis

- - - -30° from jet axis

Frequency Octave, cps

Avon Engine Noise for Several Corrugated Nozzles

Figure 43

No. of Corrugations

DEPTH OF CORRUGATIONS 2.65 INS.

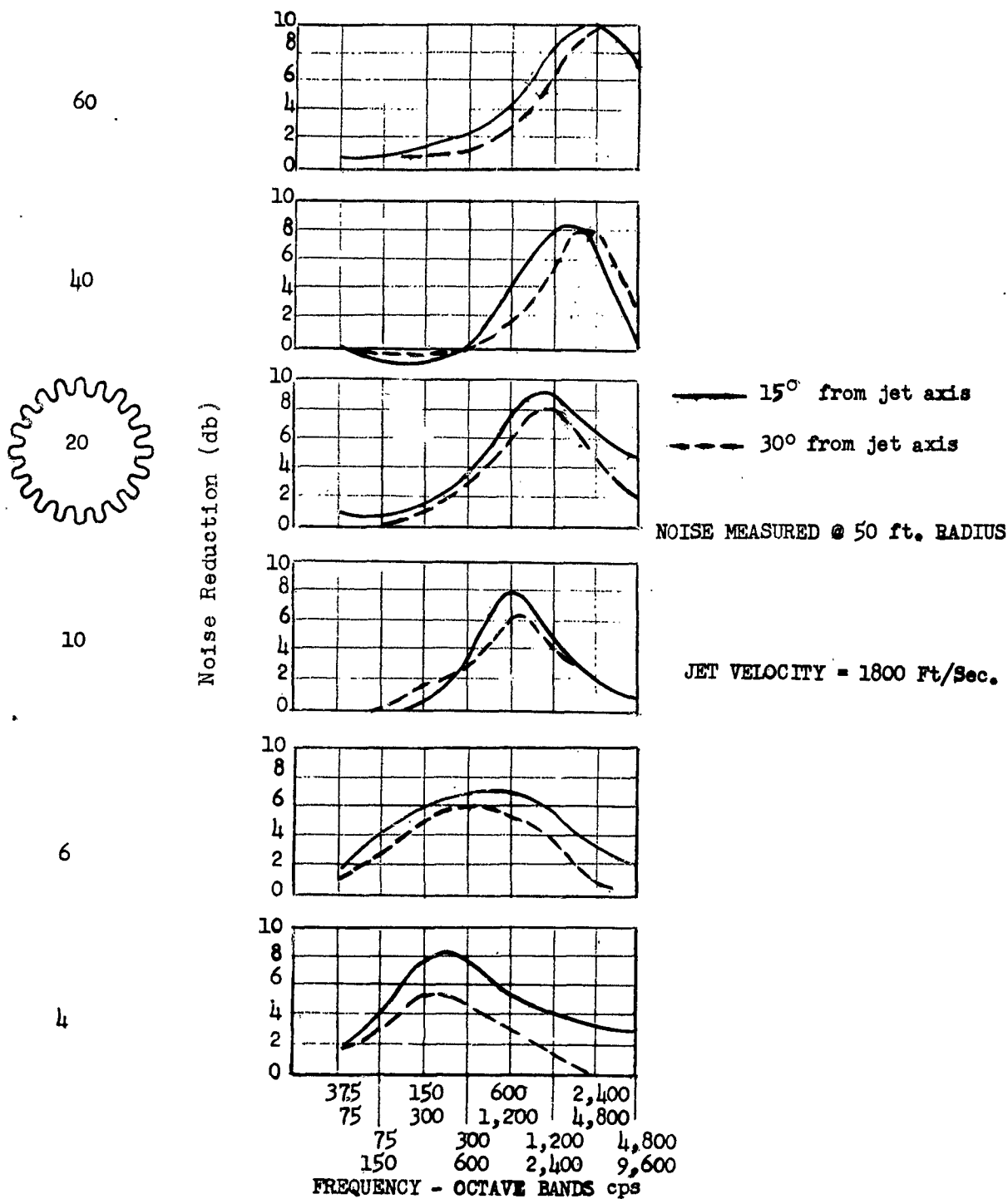
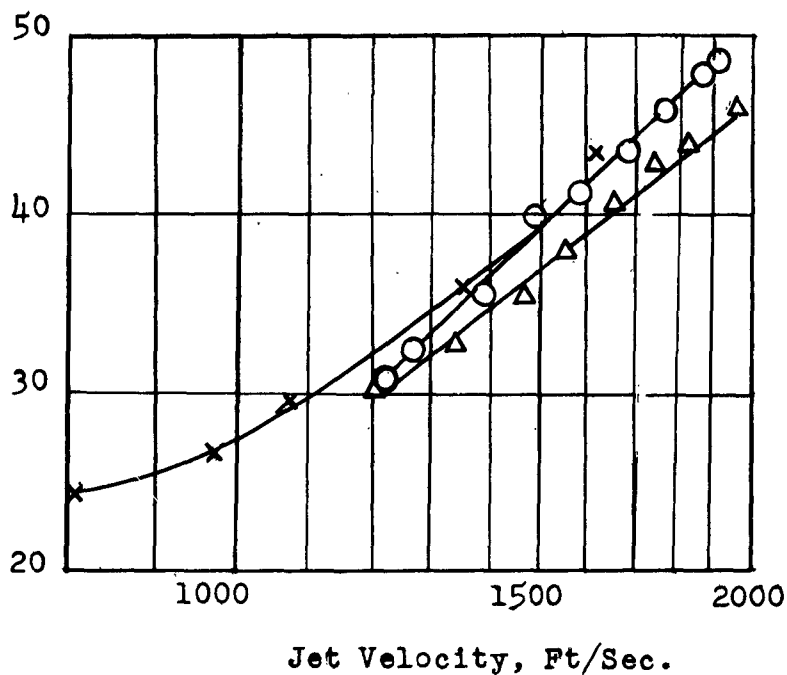


Figure 44 - The Effect of the Number of Corrugations upon Avon Engine Noise
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$$10 \log_{10} \left[\frac{\text{Acoustic Power}}{(\text{Relative Density})^2 \times (\text{Jet Area})} \right] \text{ db (re: 1 Watt/ft}^2\text{)}$$

- Avon (Standard Nozzle)
- × Derwent
- △ Avon (Corrugated Nozzle)



Total Acoustic Power Output of Various Engines with Standard & Corrugated Nozzles

Figure 46

IV. CONCLUDING REMARKS

A review and evaluation of technical efforts to date in the field of aerodynamic noise generation and control has been made to help in understanding the mechanisms of turbine engine noise. The information obtained in this survey has indicated that:

1. jet engine noise generation is primarily a result of turbulent mixing of the exhaust jet with the surrounding atmosphere. The exhaust jet velocity is the major parameter in this generation of jet noise for either choked or unchoked flow conditions.

2. at the present time, the turbine engine inlet, compressor, combustor, and turbine components are secondary sources of noise. The noise characteristics and levels of these sources are not obvious; further investigations are essential.

3. three methods are currently available for predicting the sound power levels of subsonic jets: Lighthill - $V^8 a^2$, Tyler and Perry - specific thrust, and Mercer and Dyer - K^2 . Satisfactory correlation of these methods has been obtained with full-scale jet engine sound measurements.

4. at supercritical pressure ratios, a phenomena known as screech can be encountered. The limited data indicate that screech is caused by torroidal vortices and shock wave oscillations at particular pressure ratios; frequency of screech is a function of shock spacing, pressure ratio, and nozzle diameter.

5. at supercritical pressure ratio, a convergent nozzle generates more noise than a convergent-divergent nozzle at its design pressure ratio.

6. little noise data exists for convergent-divergent exhaust nozzles. Proposed jet engines will probably operate above choked conditions at maximum, sea level, static power settings; noise characteristics of convergent-divergent nozzles require further study.

7. the laws governing the generation of noise in the near field for choked or unchoked jets have not been definitely established; this region requires more intense investigation since ground-crew personnel are exposed to the noise levels of this region.

8. the corrugated type nozzle shows the most promise in the field of subsonic jet noise suppression devices. Noise levels of full-scale engines have been reduced 8 to 10 db. This type of exhaust nozzle could be considered for flight installations.

9. research efforts should be intensified to insure the development of satisfactory jet noise suppressors which can be integrated with the engine installation and will not interfere with routine flight and ground operations of jet-powered aircraft. To date, most research efforts in this field have led to the development of suppression devices which are only feasible for ground run-up operations.

10. little data is available for suppression devices for full-scale engines operating above choked flow conditions.

11. the comparative merits of the by-pass engine as regards noise level, require further investigation.

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APPENDIX A

Sound is an auditory sensation which is experienced by the ear as a result of a disturbance in the atmosphere. This disturbance causes a pressure variation to propagate (in a wave motion) through an elastic medium such as air. Air, which has only one coefficient of elasticity, can propagate only one type of wave, longitudinal waves, in contrast to solids, which having more than one coefficient of elasticity can propagate several wave forms at the same instant. The pressure fluctuation or wave acts upon the inner ear causing the sensation of sound to be transmitted to the brain, by means of a remarkable nerve membrane system. The human ear is quite sensitive to pressure fluctuations, which can range from the weakest value of $0.0002 \text{ dynes/cm}^2$ to about the largest safe value of 200 dynes/cm^2 . At these very low pressures, the eardrum moves less than 10^{-19} cm , less than one-tenth the diameter of a hydrogen atom.

APPENDIX B

Calculation of Acoustic Power

The noise from a jet is usually defined in terms of its total radiated power, its distribution of power with frequency, and its distribution of power in space. The actual calculation of the total acoustic power is usually based upon the following assumptions:

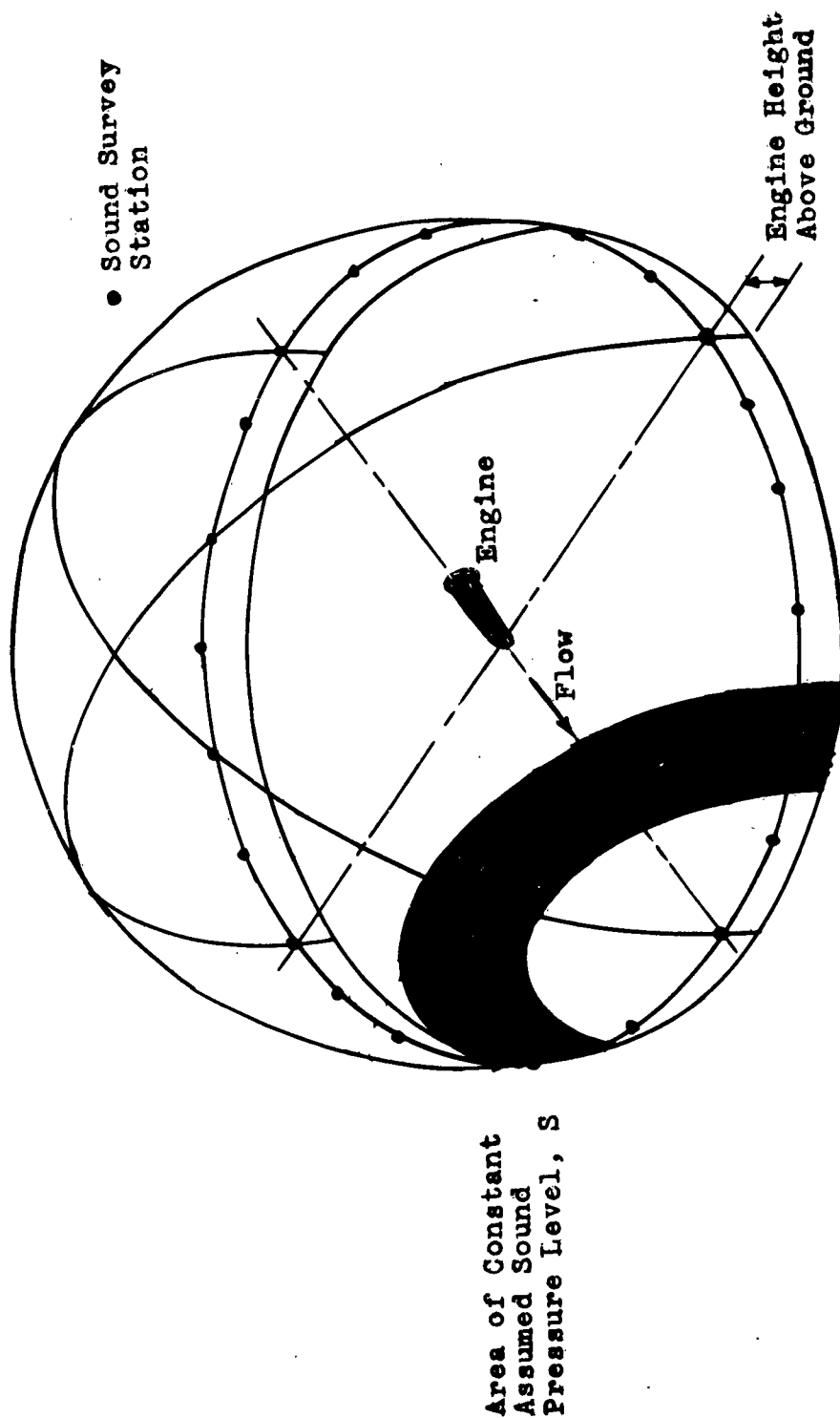
- a. The nozzle is surrounded by a spherical control surface through which passes all the radiated power. (See Figure 47.)
- b. The origin of the spherical surface is located at the center of the nozzle exit.
- c. The ground acts as a perfect reflector.
- d. The sound field is symmetric about the jet's axis.
- e. The sound pressure level measured in each portioned area, S, is assumed constant.

Nomenclature

Sound power passing through area S = W_s (watts)
Sound pressure level = SPL (db--re: 2×10^{-4} dynes/cm²)
Density of ambient air = ρ (g/cm³)
Sonic speed for ambient air = c (cm/sec)
Area = S (sq. ft.)

Procedure

- (1) $W_s = \frac{372S}{\rho c} \times 10^{-14} \text{ antilog}_{10} \frac{\text{SPL}}{10}$
- (2) Total acoustic power = $W = \sum W_s$
- (3) $\text{PWL} = 10 \log_{10} \frac{W}{W_0}$, db where $W_0 = 10^{-13}$ watts.



Sketch Illustrating Surface Used for Calculations of Sound Power Level Radiated by Engine

Figure 47

APPENDIX C

Annoyance Criteria of Jet Noise

The annoying and interfering features of intense noise upon conversation is familiar to all of us. It is desirable in many instances to be able to predict the degree of this annoyance. For example, if a new machine is to be purchased, or if an office is to be relocated, or if an airport site is to be selected, the extent of annoyance upon personnel must be predicted or a criterion for acceptable background sound levels should be established.

A method has been proposed by Beranek (32,33) to determine the interference of noise upon conversational speech. It is referred to as the Speech Interference Level and serves as a criteria which can indicate whether conversation will be heard in a jet noise field. Based upon a number of subjective tests, it has been found that the three octave bands of 600-1200, 1200-2400, and 2400-4800 cps are important frequencies for making speech comprehensible. The arithmetic average of the sound pressure levels of these three bands gives the approximate interfering effect of the noise upon communication. This number is known as the speech interference level or SIL. Table 1 indicates the required levels for communication between a listener and speaker. In computing the SIL rating, if the sound pressure level in the 300-600 cps band is found to be greater than the 600-1200 cps band by 10 db then it should be averaged with the other three bands to obtain the speech interference level.

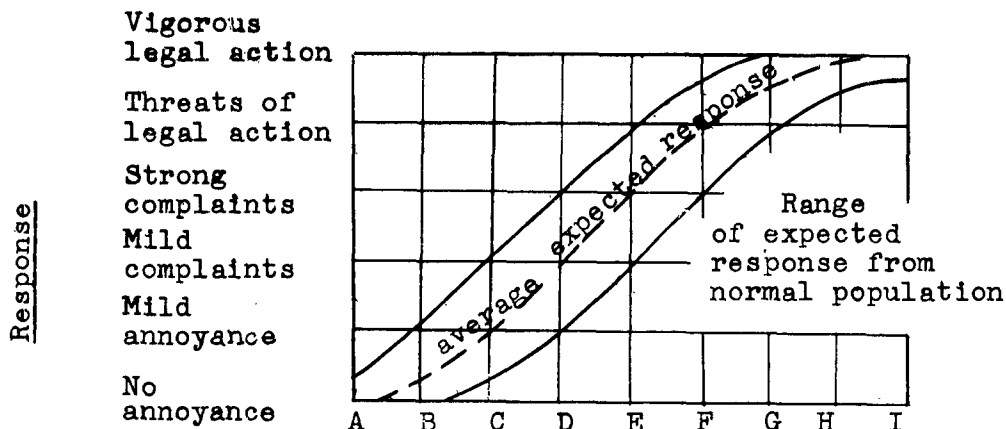
Another important item of interest is how will jet noise affect the neighbors. In what way will they react? In order to determine or predict this response, the concept of "noise rating letter" is used. This is based upon a statistical study of previous case histories involving jet noise complaints. This data has been related to community response by a curve known as the Response Curve (Figure 48). The ordinate of this curve is scaled to show various types of reactions to noise such as no annoyance, mild annoyance, strong complaints, threats of legal action, and strong actual legal action, while the abscissa indicates the corresponding noise field rating and is designated by a letter. The noise field rating is determined from the noise level rank curve (Figure 49) as follows:

- a. Plot the jet noise spectrum upon the noise level rank curve.
- b. Note the highest noise level rank zone into which the spectrum intrudes.
- c. Correct this level rank number for the spectrum characteristics by upgrading or downgrading the noise level rank by the amount indicated in Table 2. This corrected letter is the noise rating value for the particular jet noise field.

- d. Enter Figure 48 of the Response Curve and find the probable response which the noise field will create.

Table 1. Speech Interference Level Criteria

SIL	Voice Level	Nature of Possible Communication
45	Normal voice at 10 ft.	Relaxed conversation (private offices)
55	Normal voice at 3 ft. Raised voice at 6 ft. Very loud voice at 12 ft.	Continous communication in working area (business, secretarial, control rooms of test cells)
65	Raised voice at 2 ft. Very loud voice at 4 ft. Shouting at 8 ft.	Intermittent communication
75	Very loud voice at 1 ft. Shouting at 2 to 3 ft.	Minimal conversation (danger signals, pre-arranged signals required)



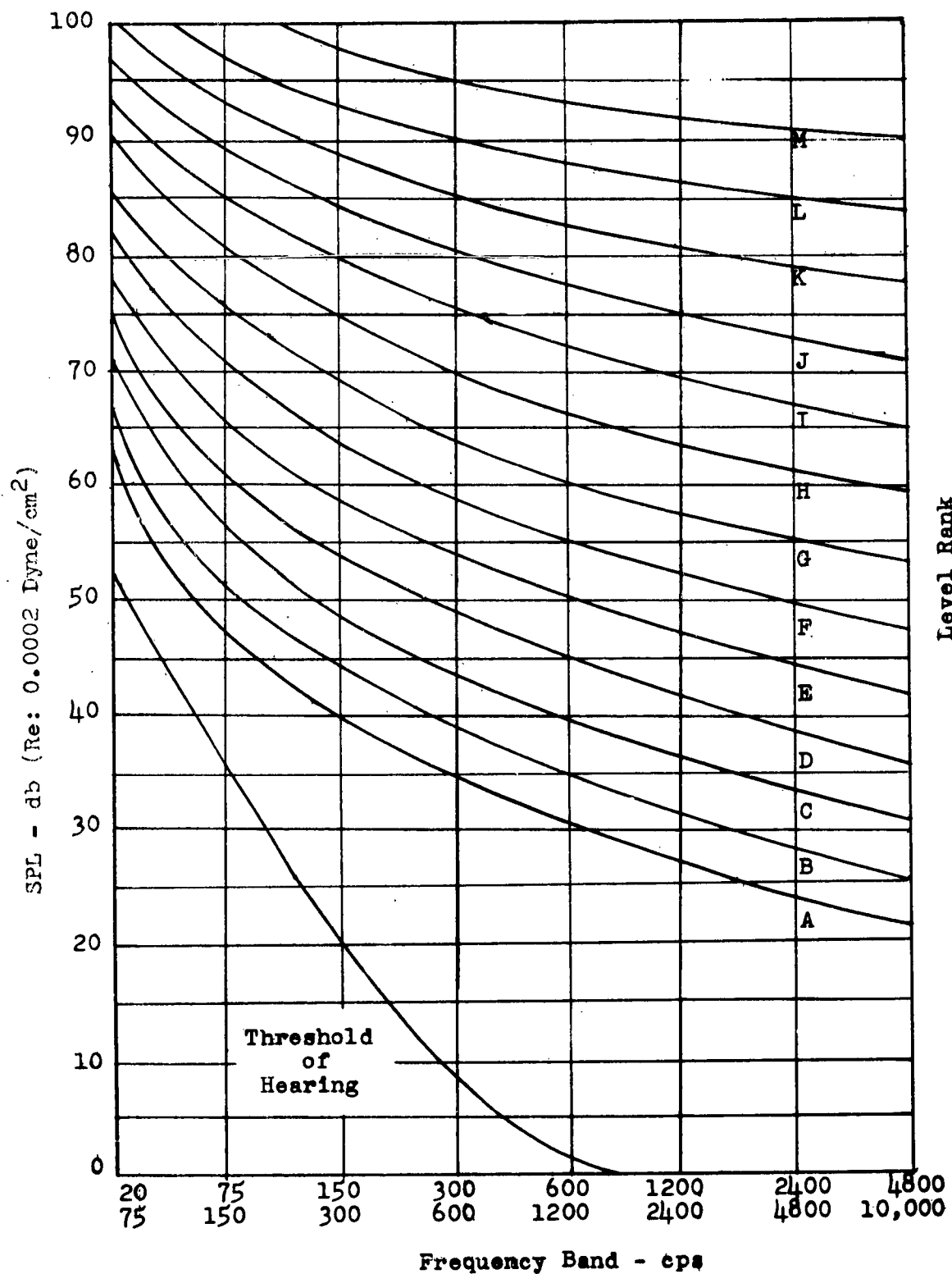
Noise Response Curve - Figure 48

Noise Rating

Background Noise

TABLE 2. List of Correction Numbers to Be Applied to Level Rank to Give Noise Rating

<u>Influencing Factor</u>	<u>Possible Conditions</u>	<u>Correction No.</u>
Spectrum character	Continuous	0
	Pure-tone components	+1
Peak factor	Continuous	0
	Impulsive	+1
Repetitive character (20-to 30-sec exposures assumed)	One exposure per min (or continuous)	
	10-60 exposures per hr	-1
	1-10 exposures per hr	-2
	4-20 exposures per day	-3
	1-4 exposures per day	-4
	1 exposure per day	-5
Background noise	Very quiet suburban	+1
	Suburban	0
	Residential urban	-1
	Urban near some industry	-2
	Area of heavy industry	-3
Time of day	Daytime only	-1
	Nighttime	0
Adjustment to exposure	No previous exposure	0
	Considerable previous exposure	-1
	Extreme conditions of exposure	-2



Noise Level Rank Curve

Figure 49